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NASA CR-
160368

Orientation Briefing

D180-24735-1

(NASA-CR-160368) SOLAR POWER SATELLITE SYSTEM DEFINITION STUDY (Boeing Aerospace Co., Seattle, Wash.) 161 p HC A08/MF A01 CSCL 22B

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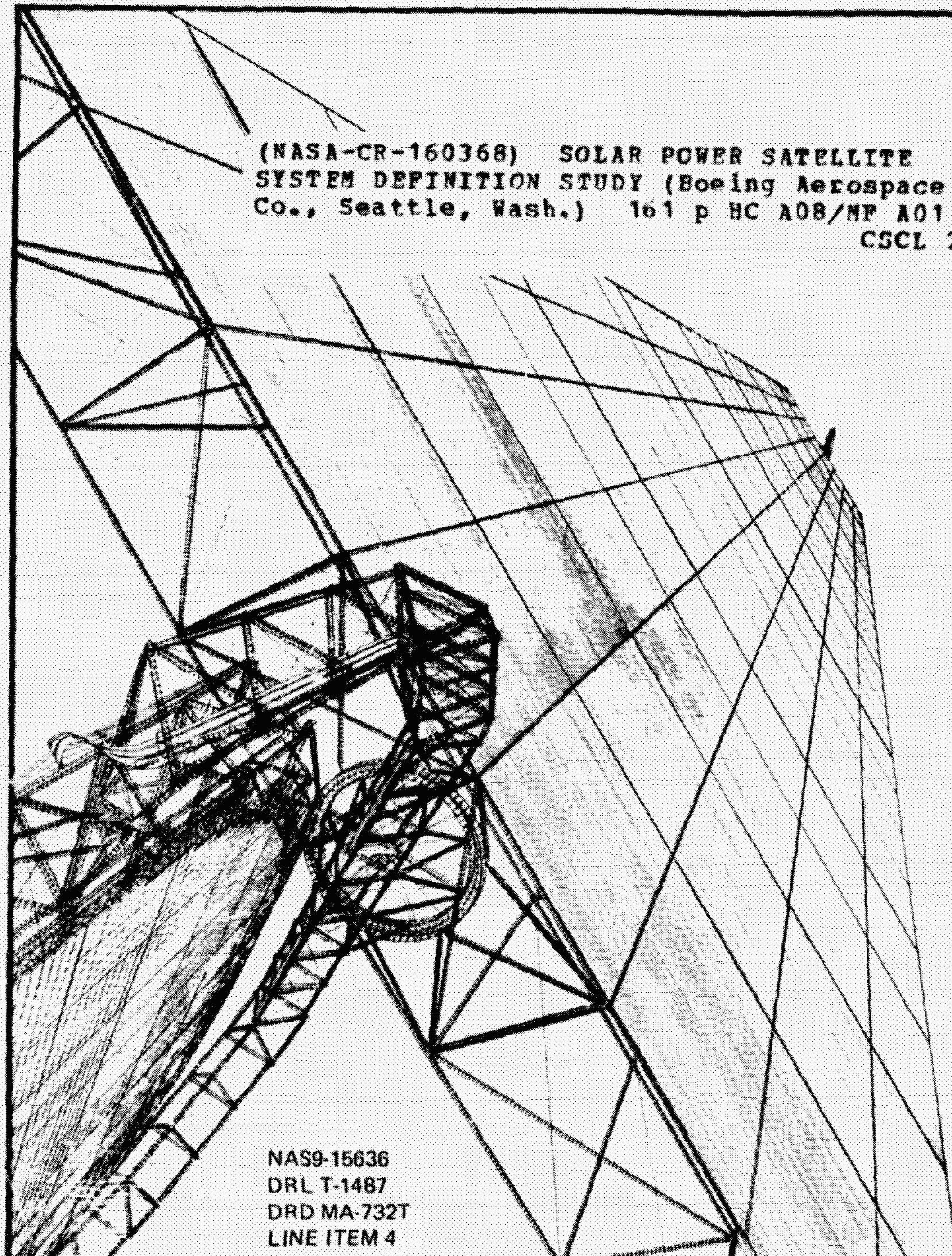

Solar Power Satellite System Definition Study

BOEING

GENERAL ELECTRIC

GRUMMAN

Arthur D Little Inc

TRW

NAS9-15636
DRL T-1487
DRD MA-732T
LINE ITEM 4

Solar Power Satellite
System Definition Study

ORIENTATION BRIEFING

D180-24735-1

July 26, 1978

Approved By: G.R. Woodcock
G. R. Woodcock
Study Manager

Boeing Aerospace Company
Ballistic Missiles and Space Division
P.O. Box 3999
Seattle, Washington 98124

AGENDA

This briefing includes a synopsis of the study plan and changes therein but primarily presents early task progress in certain key areas.

Agenda

STUDY PLAN CHANGES

EARLY TASK PROGRESS

- LASER ANNEALING
- SOLID STATE POWER AMPLIFIER
- RECTENNA OPTIONS
- INDEPENDENT ELECTRIC OTV AND CONSTRUCTION
- 2.5 GW SPS (BOEING IR&D)

STUDY ADDRESSES MULTIPLE ISSUES

The study addresses issues in three main areas:

(1) Variations and options to the current reference design; baseline definition updates.

(2) End-to-end system operations.

(3) Programmatics, emphasizing development planning through all phases of system development.

Study Addresses Multiple Issues:

Systems Definition, Operations, Programmatics

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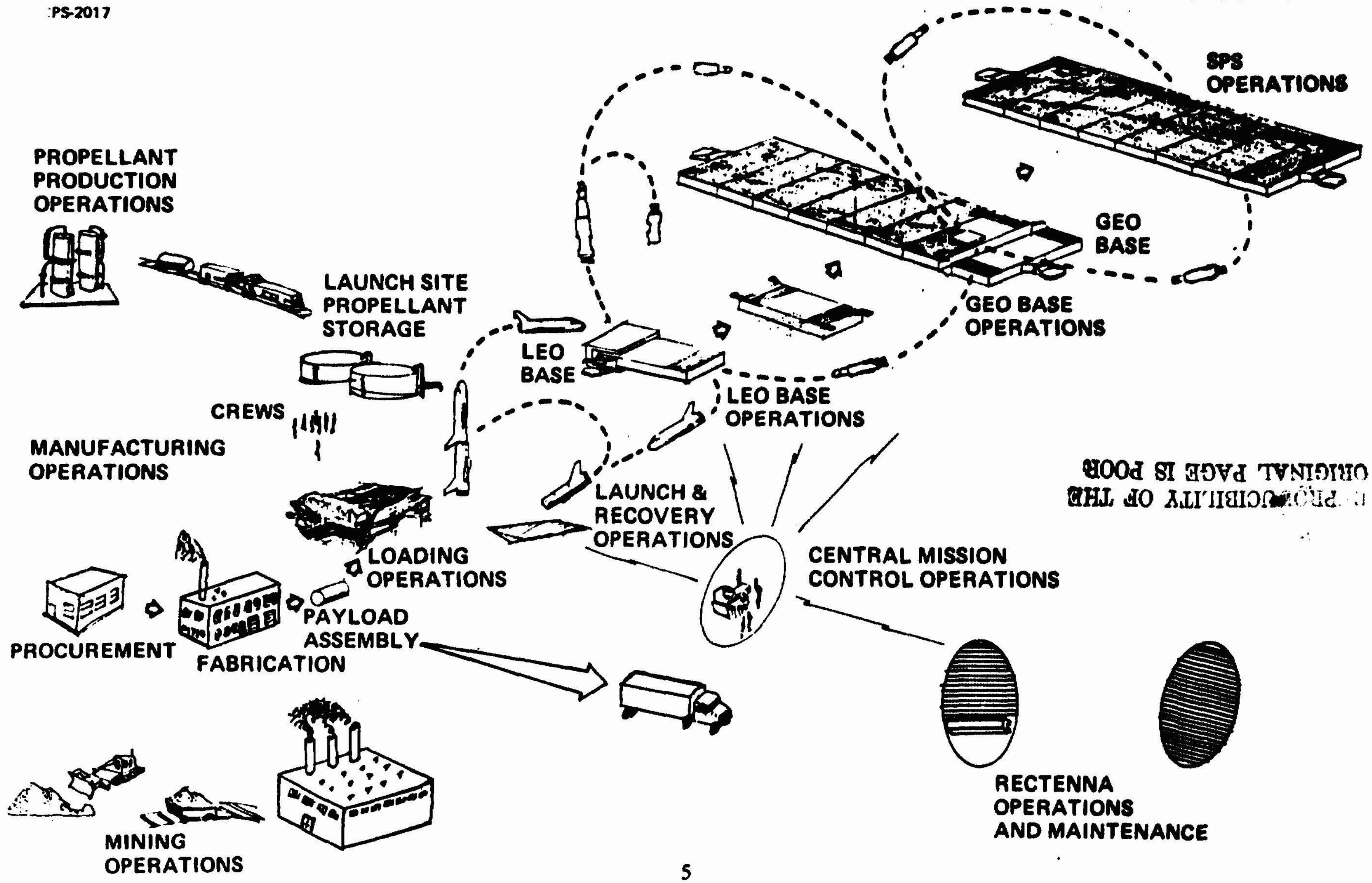
SPS-2017



STUDY PLAN OVERVIEW

The study is divided into two phases; the first to last 7 months and the second to last 9 months. The first phase is primarily directed to investigating issues and questions that have arisen in the course of prior study. In addition, a preliminary development plan will be created, emphasizing the ground-based technology advancement effort.

Phase II is mainly an end-to-end operations analysis. In addition, some definition activity will take place on the construction systems and the SPS program planning will be worked in more depth, supported by a complete update of all cost analyses

Study Plan Overview

SPS-2024

	PHASE I	PHASE II
4.1	CRITIQUE-MODIFY-MAINTAIN BASELINE SYSTEMS	UPDATE BASED ON OPERATIONS ANALYSIS
4.2	REFINE CONSTRUCTION AND MAINTENANCE APPROACHES	REFINE CONSTRUCTION EQUIPMENT AND BASE SYSTEMS; UPDATE BASED ON OPERATION ANALYSIS
4.3	DEFINE PRODUCTION CAPACITY ISSUES	DEFINE INDUSTRIAL COMPLEX AND EARTH TRANSPORTATION SYSTEMS
4.4	LAUNCH SITE SELECTION	LAUNCH SITE OPERATIONS AND LAUNCH SITE DEFINITION
4.5	DEFINE MISSION AND OPERATIONS CONTROL CONCEPTS	OVERALL OPERATIONS
4.6	DEFINE RECTENNA SITING	ANALYZE INTEGRATION OF SPS WITH GROUND NETWORK
4.7	PRELIMINARY DEVELOPMENT PLANS; DEVELOPMENT ISSUES AND OPTIONS	PREPARE TECHNOLOGY ADVANCEMENT, DEVELOPMENT, AND FACILITY REQUIREMENTS AND PLANS
4.8	UPDATE PART III COSTS	COST ANALYSIS AND SCHEDULE ANALYSIS

PRINCIPAL STUDY PLAN CHANGES

As a result of contract negotiations, a number of changes were made to the study plan. The most important of these are summarized here.

Principal Study Plan Changes

- PHASE I/II LENGTHS ARE NOW 7 AND 9 MONTHS RATHER THAN 6 AND 10
- ADDED TO PHASE I:
  - CRITIQUE NASA BASELINE AND PREPARE SYSTEM DESCRIPTION
  - ANALYZE NON-COMPOSITE ANTENNA AND SOLAR ARRAY STRUCTURE
  - ANALYZE SOLID STATE POWER TRANSMITTER
  - DEVELOP LONG-LIFE POWER PROCESSOR CONCEPT
  - INDEPENDENT ELECTRIC OTV ANALYSIS
  - SMALL ADDITIONAL EFFORT ON SOLAR CELL ANNEALING AND POWER TRANSMITTER THERMAL ANALYSIS
  - EXTENSION OF JSC MPTS ARRAY COMPUTER PROGRAM CAPABILITY
  - INITIAL SPS DEVELOPMENT PLAN OUTPUT
- DELETED FROM PHASE I:
  - INLAND LAUNCH SITES AND DOWNRANGE LAND LANDING BOOSTERS (TASK 4.4)
  - MOST OF MAINTENANCE ANALYSIS DEFERRED TO PHASE II
  - GENERAL CRITIQUE OF THE CURRENT REFERENCE DESIGN
  - PHASE CONTROL SYSTEM ANALYSIS (USE LINCOM RESULTS)

STUDY ORGANIZATION

On this chart, the study organization is matrixed with study tasks and technical disciplines, showing primary responsibilities and chains of communication.

SPS

SPS-2026

Study Organization

DISCIPLINES (TASK)	BOEING	GENERAL ELECTRIC	GRUMMAN	TRW	A. D. LITTLE
STUDY MANAGEMENT AND DOCUMENTATION (4.9)	G. R. WOODCOCK	R. ANDRYCZYK	R. McCAFFREY	R. CRISMAN	P. GLASER
SATELLITE DEFINITION (4.1.1) (4.1.3) INTEGRATE TASK 4.1	J. GEWIN O. DENMAN R. CONRAD (WTS)	P. FOLDES	R. McCAFFREY 4.1.1	R. CRISMAN J. HIEATT 4.1.1	P. CHAPMAN
INDUSTRIAL OPERATIONS AND LOGISTICS (4.3.1, 4.3.2, 4.3.3, 4.5.1) INTEGRATE TASK 4.3	K. PROCTOR				P. CHAPMAN 4.3 ALL
SPACE OPERATIONS AND CONSTRUCTION (4.2.1, 4.2.3, 4.3.4, 4.5.3, 4.5.4, 4.5.5) INTEGRATE TASKS 4.2 & 4.5	E. DAVIS (CONSTR & INTEGRATION) K. MILLER (OPS)	B. KAUPANG 4.2.3	M. ROMANELLI G. HARMS R. PRATT 4.2.1 4.5.4 4.5.5	R. MORRIS J. HIEATT 4.5.3	
LAUNCH SITE DEFINITION (4.4 ALL, 4.5.2) INTEGRATE TASK 4.4	H. DIRAMIO J. JENKINS				
MICROWAVE AND RECTENNA (4.1.1 SUPPORT, 4.7 SUPPORT, 4.2.2)	E. NALOS W. LUND	B. KAUPANG P. FOLDES			
GRID OPERATIONS (4.2.2, 4.6 ALL) INTEGRATION TASK 4.6	D. GREGORY	B. KAUPANG			
TECHNOLOGY ADVANCEMENT AND DEVELOPMENT (4.7 ALL) INTEGRATE TASK 4.7	D. GREGORY O. DENMAN	R. ANDRYCZYK	R. McCAFFREY	R. CRISMAN	
COSTS AND SCHEDULES (4.8 ALL) INTEGRATE TASK 4.8	L. SLIGER		R. McCAFFREY		P. CHAPMAN (REVIEW)

GENERAL ELECTRIC

The principal task responsibilities for General Electric are summarized here.

General Electric

- PROVIDE SUBARRAY DESIGN INTEGRATION FOR LINCOM PHASE CONTROL SYSTEM HARDWARE.
- PROVIDE RECTENNA POWER CONDITIONING ANALYSIS.
- PROVIDE RECTENNA FAILURE MODE AND EFFECTS, CONSTRUCTION, AND MAINTENANCE ANALYSES.
- PROVIDE SATELLITE/RECTENNA/UTILITY GRID INTEGRATION CONCEPTS AND OUTAGE ANALYSIS.
- PROVIDE INPUTS FOR TECHNOLOGY ADVANCEMENT DEVELOPMENT, AND FACILITY REQUIREMENTS

GRUMMAN

The principal task responsibilities for Grumman are summarized here.

Grumman

- ANALYZE ALUMINUM SOLAR ARRAY STRUCTURE
- PROVIDE CRITIQUE OF, AND ANALYZE ALTERNATIVE APPROACHES TO SPACE CONSTRUCTION APPROACH.
- ASSIST WITH CONSTRUCTION BASE OPERATIONS PLANS AND BASE DEFINITION CONCEPTS.
- PROVIDE INPUTS IN THE CONSTRUCTION AREA FOR THE SPS DEVELOPMENT PLAN.
- PROVIDE INPUTS FOR TECHNOLOGY ADVANCEMENT, DEVELOPMENT, AND FACILITY REQUIREMENTS.

TRW, INC.

The principal task responsibilities for TRW, Inc. are summarized here.

TRW

- PROVIDE CRITIQUE OF REFERENCE OF MPTS INTEGRATION AND PHASE CONTROL
- DEVELOP CONCEPTS FOR ON-BOARD DATA PROCESSING AND COMMUNICATIONS SYSTEMS
- ANALYZE MISSION CONTROL OPERATIONS

A. D. LITTLE CO.

The principal task responsibilities for A.D. Little Co. are summarized here.

Arthur D. Little

- PROVIDE CRITIQUE OF THE NASA COMPROMISE DESIGN.
- PROVIDE DEFINITION OF THE INDUSTRIAL COMPLEX AND EARTH TRANSPORTATION SYSTEM.
- PROVIDE CRITIQUE OF BOEING DEVELOPED COST AND SCHEDULE ANALYSES AND PROGRAM PLANS.

Laser
Annealing

ADVANTAGES OF LASER ANNEALING

Silicon solar cell performance degrades in the presence of particular radiation such as that in the geosynchronous environment of SPS. The reduced performance is the result of recombination centers that have been generated in the orderly silicon lattice. The repair of this damage requires the solar cell damaged region to be heated to an elevated temperature for a sufficient length of time to restore the orderly crystalline lattice. This process is commonly referred to as solar cell annealing.

Annealing radiation damage from silicon solar cells has been accomplished by three processes: 1) thermal bulk annealing, 2) electron beam annealing, and 3) laser beam annealing. Both the thermal bulk and electron beam annealing processes require the annealing unit to be physically closc to the solar cells for proper operation.

A basic description of the laser beam is noted on this chart along with the desirable characteristics of laser annealing. The laser wavelength can be chosen such that the energy is deposited at the desired depth in the silicon or in the cover to heat the cell by conduction. The laser beam does not need to be physically close to the solar blanket since the beam is highly directional and the light is coherent. Tests have shown that laser annealing is effective.

Advantages of Laser Annealing

- CONVERTS SOME FORM OF ENERGY INTO LIGHT ENERGY
  - THIS LIGHT ENERGY IS–
    - HIGHLY DIRECTIONAL
    - MONOCHROMATIC
    - COHERENT
    - CAN BE GENERATED IN VARYING TIME/INTENSITY RELATIONSHIPS
      - FROM CW TO 10^{-12} sec PULSES
      - VERY LOW INTENSITY TO 10^{12} W/PULSE
- CAN BE USED TO PROVIDE HEAT ENERGY AT A DESIRED LOCATION AND AT A PREDETERMINED DEPTH IN TARGET MATERIAL
- DOES NOT HAVE TO BE PHYSICALLY CLOSE TO TARGET MATERIAL
- HAS BEEN SHOWN TO BE AN EFFECTIVE ANNEALING DEVICE

LASER COMPARISONS

Shown here are the major laser classifications and some representative examples of each. The output power and efficiency listings provide a comparison of the realistic options available. The laser wavelength is a most important parameter since it will determine where the energy will be absorbed in the blanket material.

Laser annealing tests have been performed using the 1.06 μm Nd:YAG laser and the 10.6 μm CO_2 laser. It appears that the selected wavelengths will be between these two limits. This conclusion narrows the options appreciably.

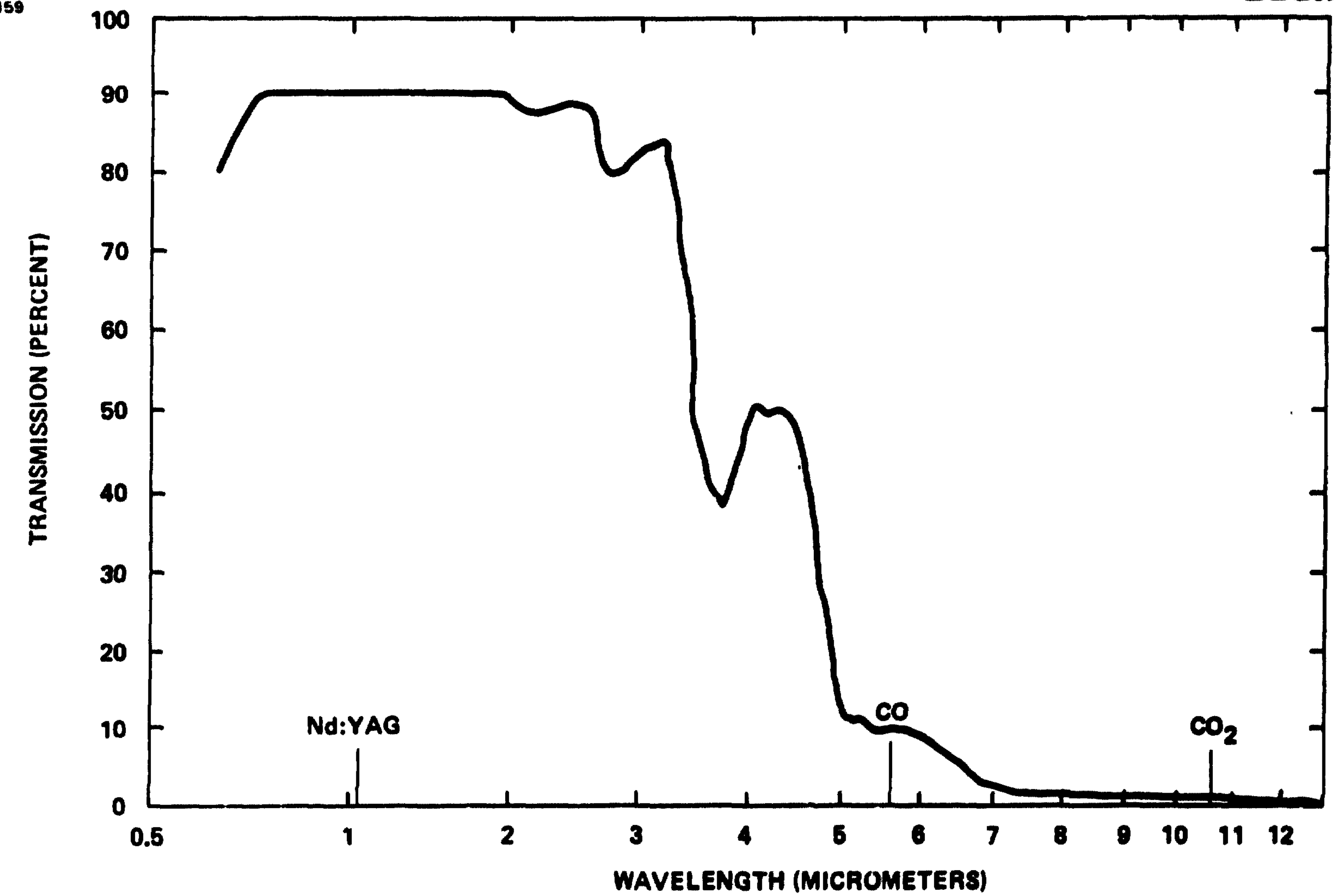
Laser Comparisons

TYPE	λ (μm)	OUTPUT	POWER (WATTS)	PULSE LENGTH (SECONDS)	EFFICIENCY
GAS					
CO_2	10.6	CW, (P)	1,000, (2×10^7)	–, $(20\,(10)^{-9})$	20%
CO	5.6	CW, (P)	–, (10^6)	–, (ms)	> 20%
He-Ne	0.6328	CW	0.05	–	0.06%
A II	0.5	CW	5	–	0.06%
Ne II	0.3324	CW	0.05	–	–
N_2	0.3371	P	$2(10)^5$	$20(10)^{-9}$	–
SOLID STATE					
RUBY	0.6943	P	$4(10)^5$, (10^9)	ms, $(20(10)^{-9})$	1%, (–)
Nd:GLASS	1.06	P	$(10)^6$, $(3(10)^9)$	ms, $(20(10)^{-9})$	1%, (–)
Nd:YAG	1.06	CW, (P)	100, 5,000	$(20(10)^{-9})$	3%, (0.2%)
INJECTION (SEMICONDUCTOR)					
GaAs	0.90	P	100	$20(10)^{-9}$	10%
GaAs (AT 77°K)	0.84	CW	1	–	20%
LIQUID					
DYE	VISIBLE INFRARED TUNABLE	P	$2(10)^6$	$20(10)^{-9}$	–

TRANSMISSION CHARACTERISTICS OF CORNING 7070 GLASS

This chart shows the effect of laser wavelength on energy deposition in the solar cell. The Nd:YAG laser energy is absorbed primarily in the solar cell whereas the CO_2 wavelength laser deposits the majority of its energy in the coverglass. Due to the differential thermal expansion characteristics between the cell and cover, a wavelength between these two should be investigated.

Transmission Characteristics of Corning 7070 Glass

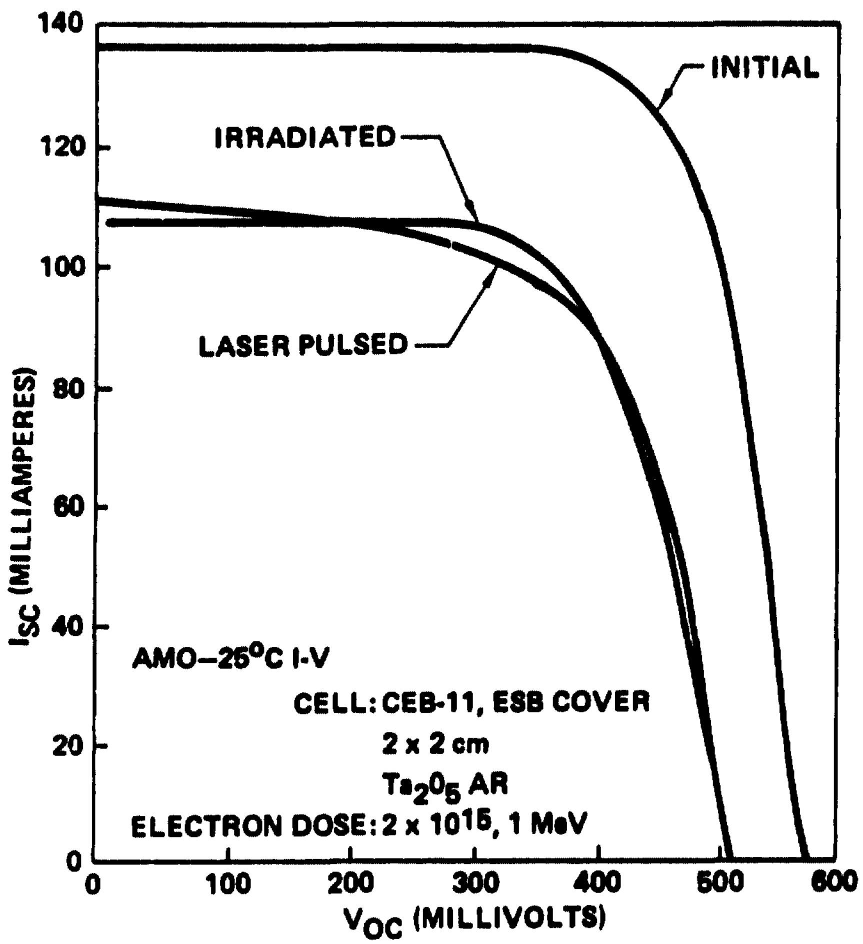


RESULTS OF SPIRE LASER ANNEALING EXPERIMENT

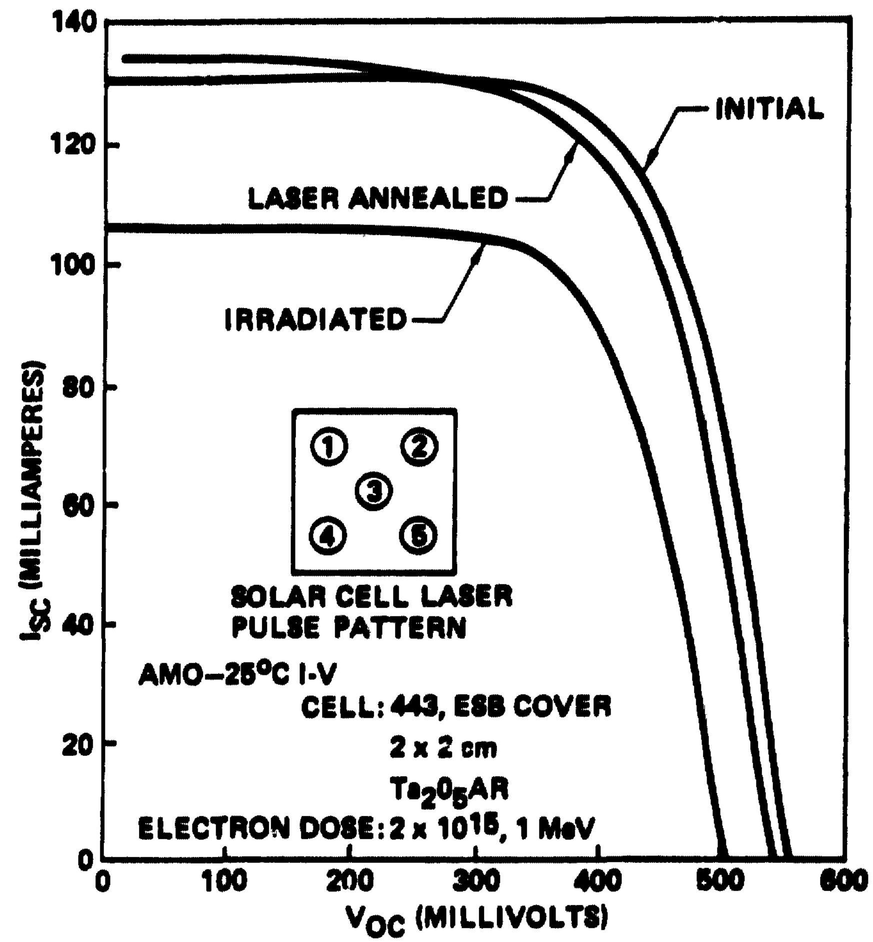
Shown here are the results of two laser annealing experiments performed by SPIRE, under subcontract. A higher energy density was attempted for the Nd:YAG laser annealing process but resulted in solar cell failures. An energy density/pulse length relationship between the one shown and that that caused failures should be investigated.

The CO_2 laser annealing experiment was highly successful even though the complete cell was not illuminated. Recall that at CO_2 wavelength the solar cell recieves the annealing energy through thermal conduction from the cover glass.

Results of SPIRE Laser Annealing Experiment



I–V HISTORY OF Nd:YAG LASER PULSED CELL



I-V HISTORY OF CO_2 LASER ANNEALED CELL

CO_2 LASER DESIGN PARAMETERS

Shown here are the design parameters for a CO_2 laser and the resulting physical characteristics for two sizes. Due to the length and high voltage of the 1000 watt laser, the 500 watt system was chosen. This results in a larger number of parts but is probably more condusive to SPS applications.

CO_2 Laser Design Parameters

POWER OUTPUT:		1,000W	500W
EFFICIENCY:		15%	15%
TYPICAL POWER OUTPUT (75 W/m):	DISCH LENGTH	13.3m	6.7m
DISCHARGE POWER INPUT (500 W/m):			
SATURATION PARAMETER (1 W/mm^2):	CAPILLARY DIAMETER (d)	35.7 mm	25.2 mm
(DISCHARGE VOLTAGE/cm) x CAPILLARY DIAMETER (d) (2,000 (V/cm) mm):	VOLTAGE	74.7 kV	52.9 kV
DISCHARGE CURRENT TO CAPILLARY DIAMETER RATIO (I/d) (2.5 mA/mm):	I	89.3 mA	63.0 mA
GAS PRESSURE TO CAPILLARY DIAMETER PRODUCT (Pd) (50 torr-mm):	P	1.40 torr	1.98 torr

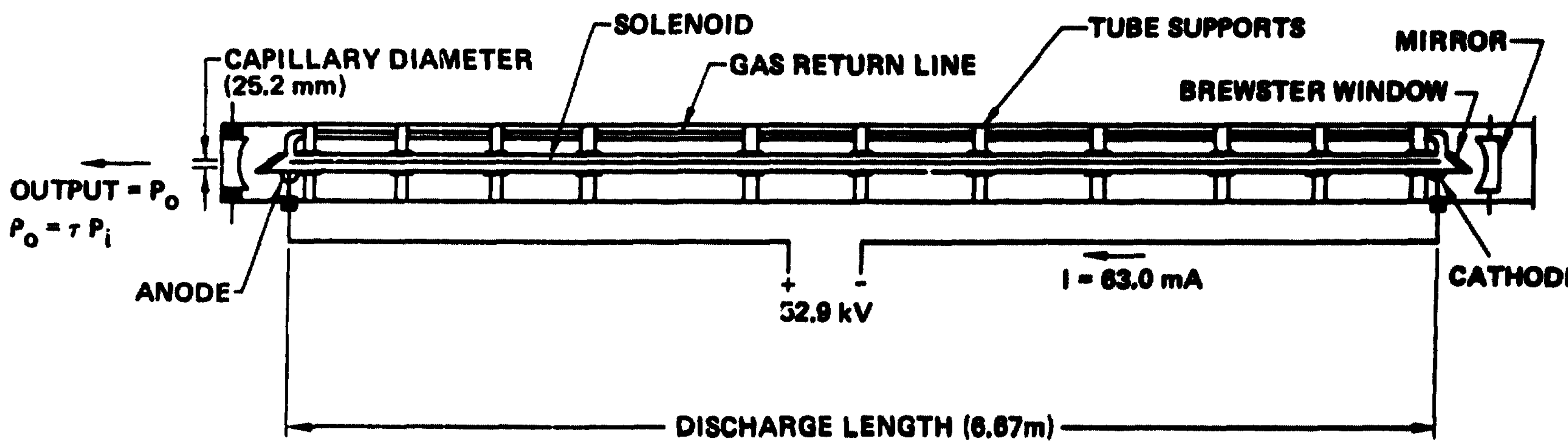
CO_2 LASER DESCRIPTION

This figure shows the basic essentials for a 500 watt CO_2 laser operation. The small diameter of the beam can be optically tailored to provide the desired illumination pattern on the solar blanket.

This device would be a flow type laser in that the CO_2 gas is moved through the tube to allow recombination and cooling. This figure shows a simple return line but in practice, with several lasers operating in parallel, a centralized accumulator and thermal control system may be desirable.

Commercial CO_2 lasers have been built that are much larger than that shown here. The application of this device to SPS requirements and improved reliability are the major areas that need further development.

CO_2 Laser Description



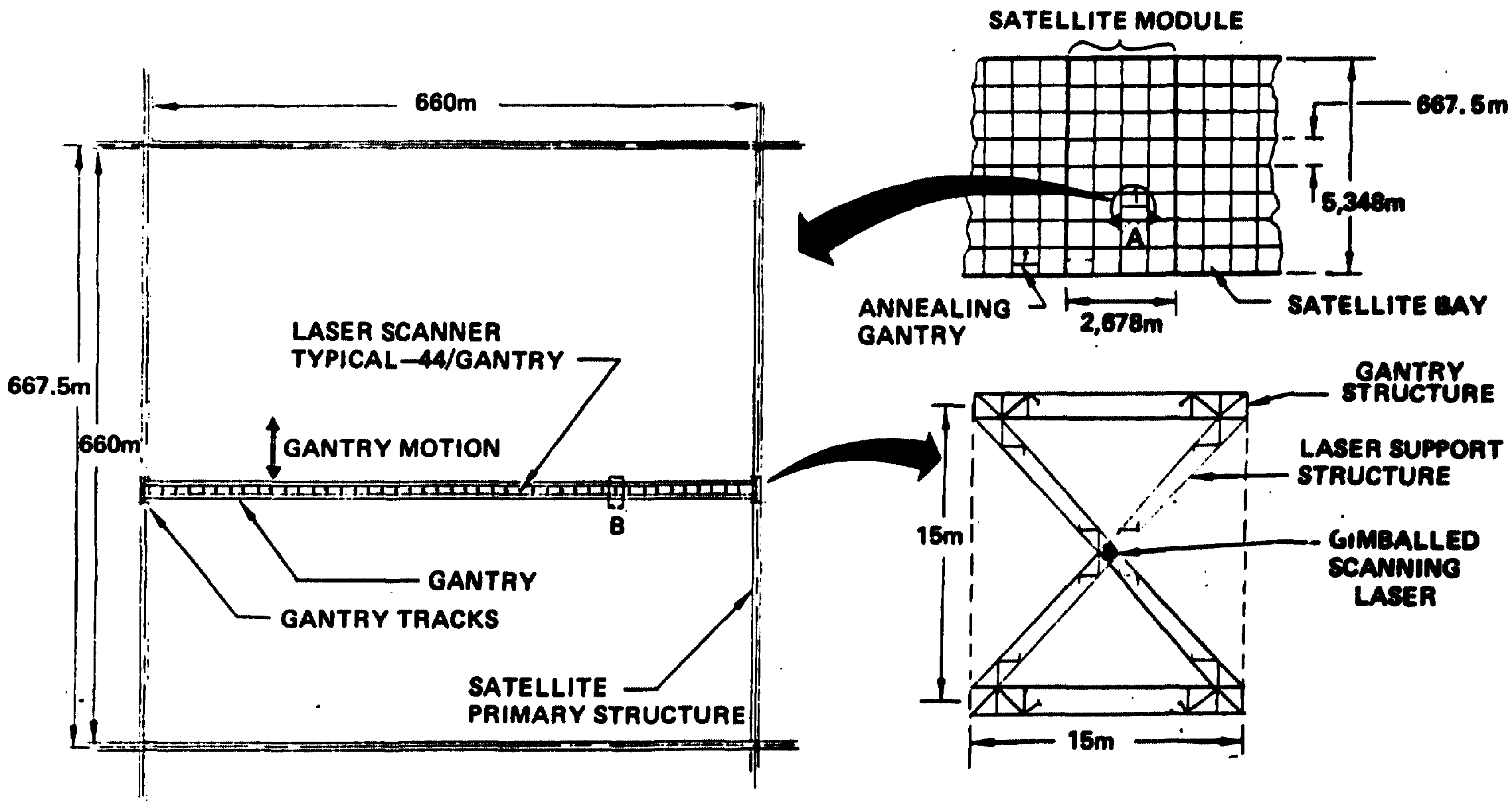
GAS PRESSURE:	1.98 torr
EFFICIENCY:	15%
POWER OUTPUT:	500W

LASER ANNEALING CONCEPT

The concept of how the actual annealing process would be accomplished is shown. Each laser gimbal would actually have 64-500 watt CO_2 lasers installed. The laser beams would be optically tailored to provide the desired illumination pattern and energy density.

The gimbals would be mounted on an overhead gantry that would span the entire bay width, one bay of solar array would be annealed in fifteen meter increments. It should be noted that the solar array strings that are undergoing annealing are nonoperational.

Laser Annealing Concept



DETAIL A
TYPICAL 667.5m BAY

DETAIL B
TYPICAL LASER ANNEALER

GIMBALLED SCANNING LASER CHARACTERISTICS

The characteristics of the SPS Laser Annealing system are shown. The timelines are for one annealing gantry operating in each satellite module. If the cost optimization of the laser annealing systems impact on SPS performance requires a faster anneal, more gantries can be installed. It should be noted that the power requirement is relatively small but the solar array being annealed is not operational.

Gimbaled Scanning Laser Characteristics

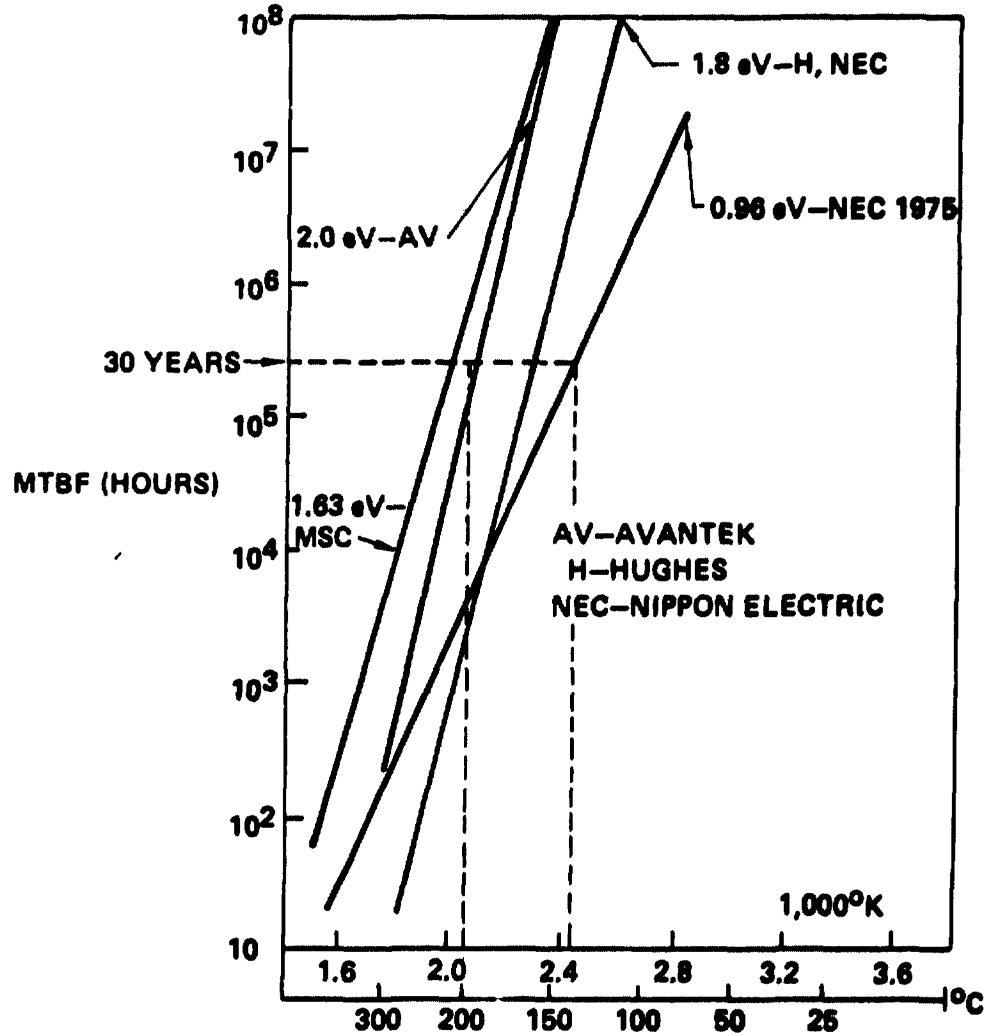
• ANNEALING ENERGY DENSITY:	128 W-sec/cm^2
• POWER DENSITY:	64 W/cm^2
• T_{MAX} (ACTIVE REGION):	550°C
• LASERS/GIMBAL:	64
• SCANNING SPOT SIZE:	500 cm^2 (44.0 x 11.4 cm)
• SPOT SWEEP RATE:	5.7 cm/s
• POWER REQUIRED/LASER GIMBAL:	213 kW
• POWER REQUIRED/GANTRY:	9.37 MW
• NUMBER OF GANTRIES/SATELLITE:	8 (1/SATELLITE MODULE)
• TOTAL ANNEALING POWER REQUIREMENT:	75 MW
• TIME REQUIRED TO ANNEAL ARRAY:	147 DAYS

Solid-State
Power Amplifier

PROJECTED LIFE OF GaAs FET TRANSISTORS

The primary motivation for development of a solid state transmitter is the long life expectancy of the solid-state amplifier devices. It is conceivable that a successfully-integrated solid-state system could approach the reliability level of the solar cell arrays, which are expected not to require replacement over the life of the SPS. The successful integration of solid-state systems, however, poses serious problems.

Projected Life of GaAs FET Transistors



MICROWAVE JOURNAL
APRIL, 1978

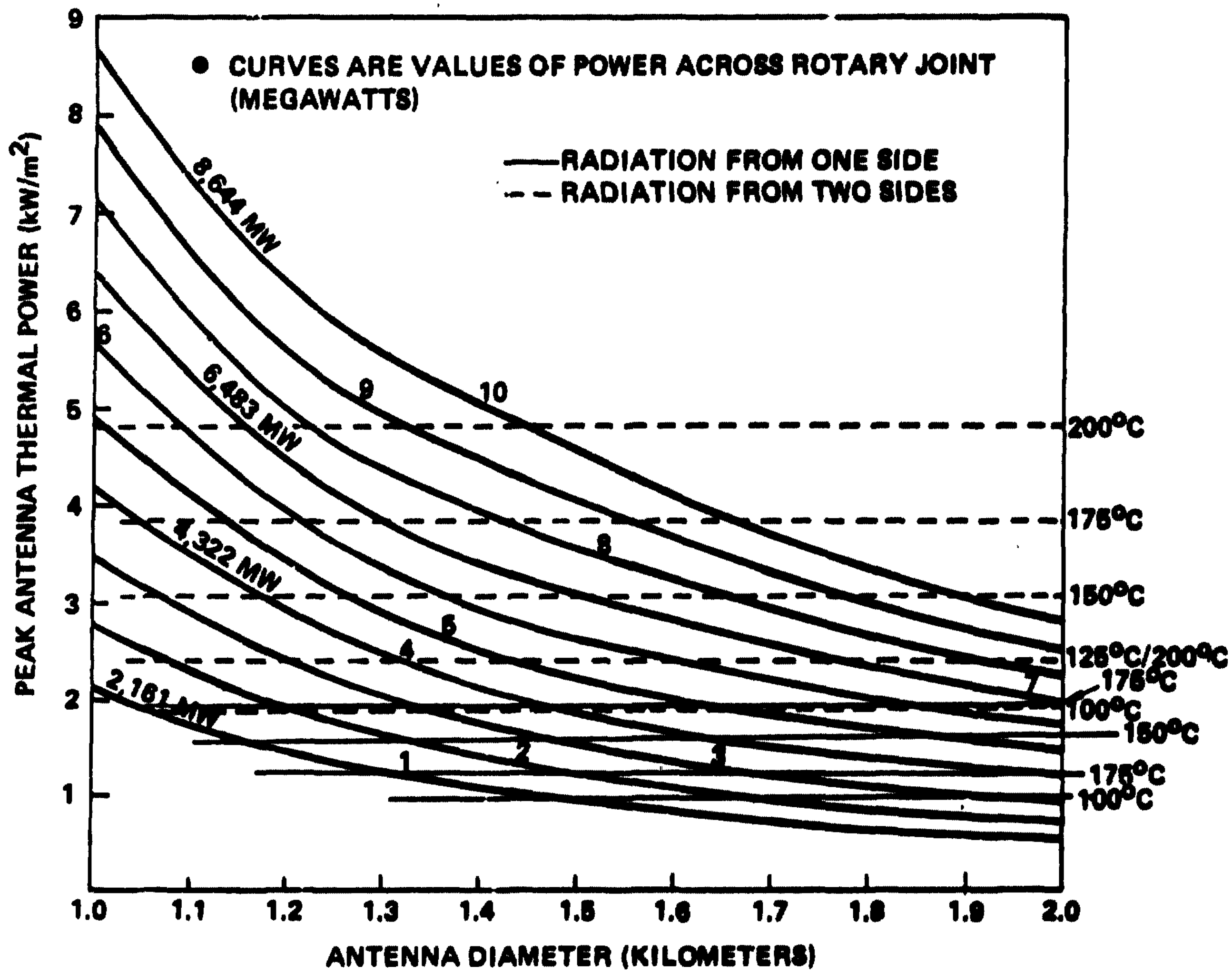
SPS SYSTEM SENSITIVITY MODEL SOLID STATE TRANSMITTER

The results exhibited here show outputs from the SPS systems sensitivity model, assuming a 71% efficient power amplifier and complete power processing of distribution voltage (40 kv) to representative solid state voltages of less than 100 volts. (A realistic penalty for the massive currents required at these low voltages was not taken). Accommodation of typical solid state temperature limits will clearly require reduction from the reference power levels of 8644 MW, or large apertures, or both.

SPS System Size Sensitivity Model

Solid State Transmitter

SPS-2136

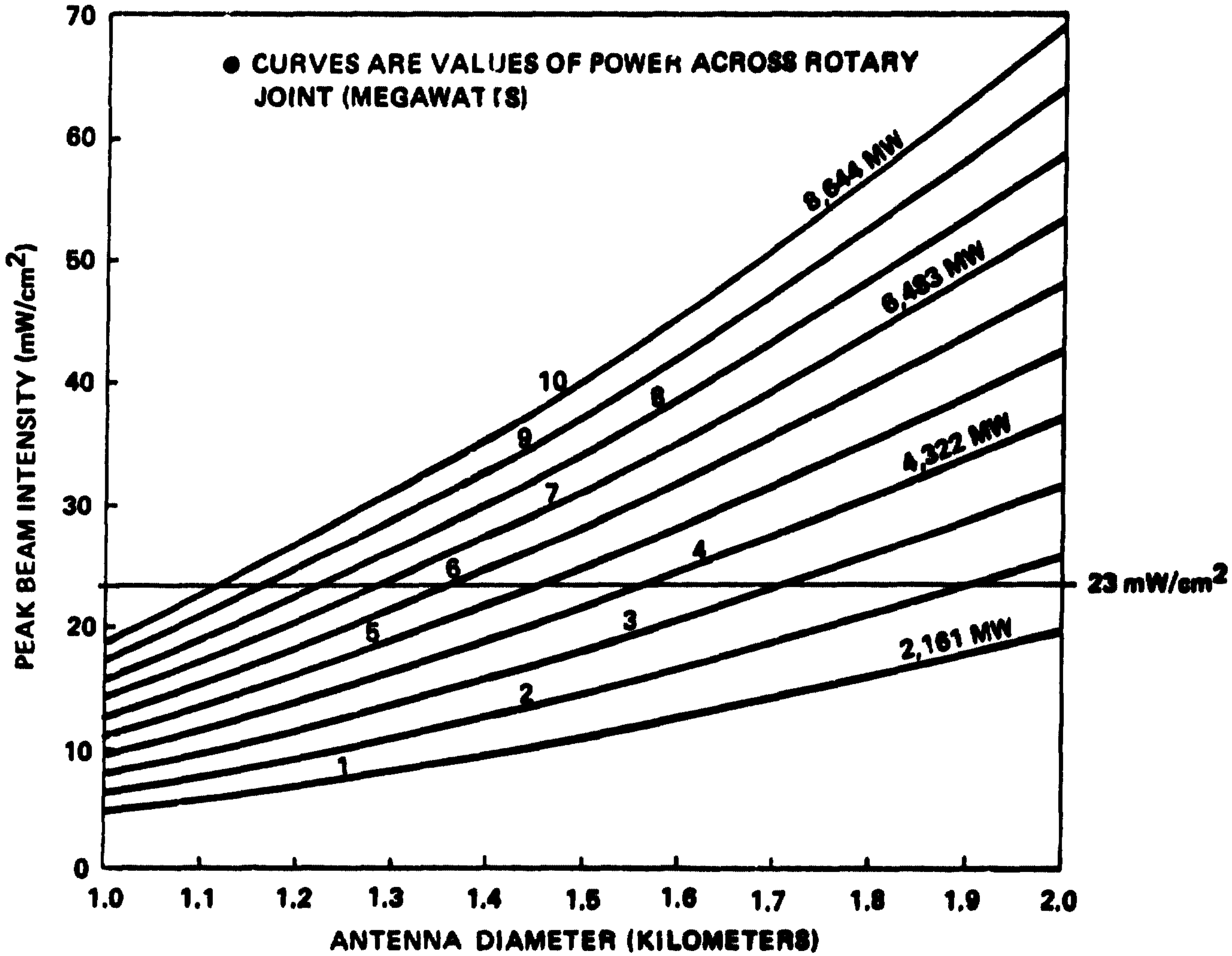


SPS SYSTEM SENSITIVITY MODEL SOLID STATE TRANSMITTER

Additional results from the same model show that severe limits are placed on combining high powers with large apertures by ionosphere heating (and perhaps other) limits on peak beam intensity at Earth.

SPS System Size Sensitivity Model
Solid State Transmitter

SPS-2137

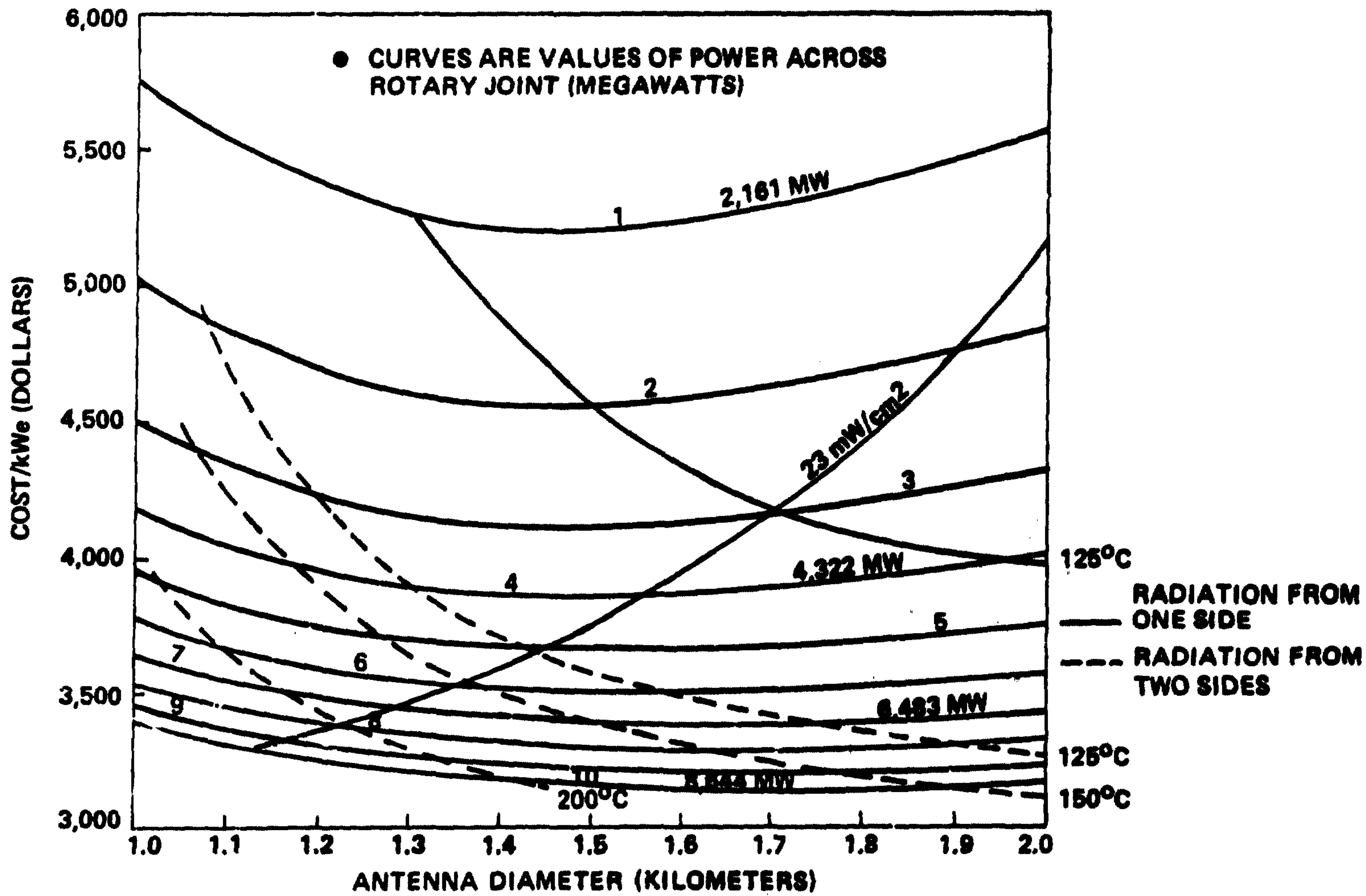


SPS SYSTEM SENSITIVITY MODEL SOLID STATE TRANSMITTER

When these constraints are combined on a cost indicator chart, it is clear that (1) the constrained optimal system will have a rotary joint transfer power less than 5000 megawatts with a transmitter aperture of about 1.5 kw; (2) the cost will be high relative to the klystron reference; (3) a strong cost motivation exists to develop a transmitter configuration that can radiate waste heat from both sides.

SPS System Size Sensitivity Model
Solid State Transmitter

SPS-2138

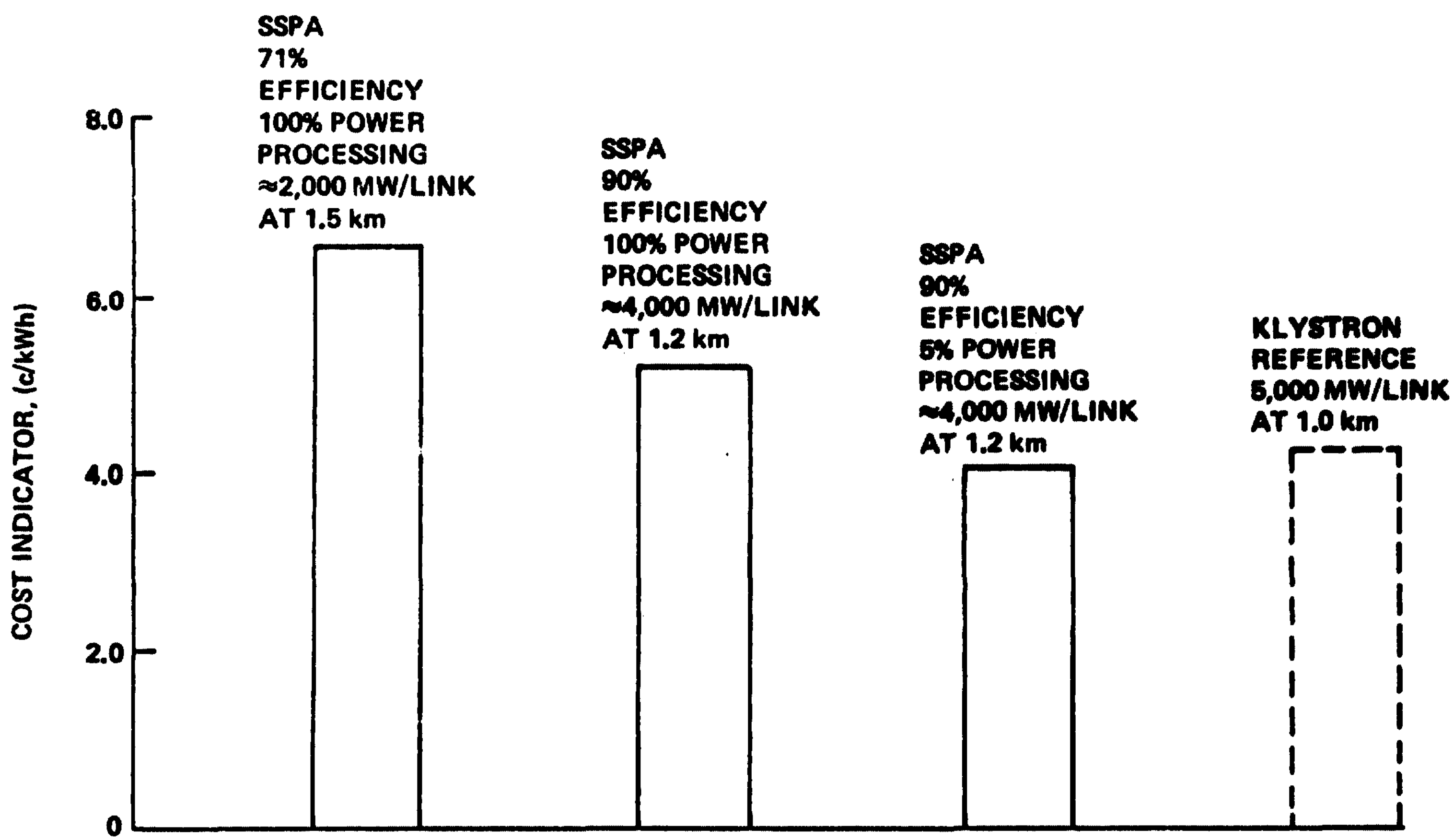


SOLID STATE POWER AMPLIFIER COST LEVERAGES

The cost inclusions of the previous chart are strongly influenced by assumptions. Since the relationships between assumptions and hardware realities are not yet entirely clear, it is important to examine the cost leverages of assumptions as is done on this chart. The efficiency and power processing inputs to the systems sensitivity model were varied as noted, with the results shown. _If_ a more efficient SSPA device/circuit could be developed, and _if_ such devices could be series/parallel connected to match high voltage dc power, a solid state transmitter competitive with or better than the klystron reference might be possible. The potential benefits are well worth the technology investigation and analysis needed to find out.

SPS-2180

Solid State Power Amplifier Cost Leverages



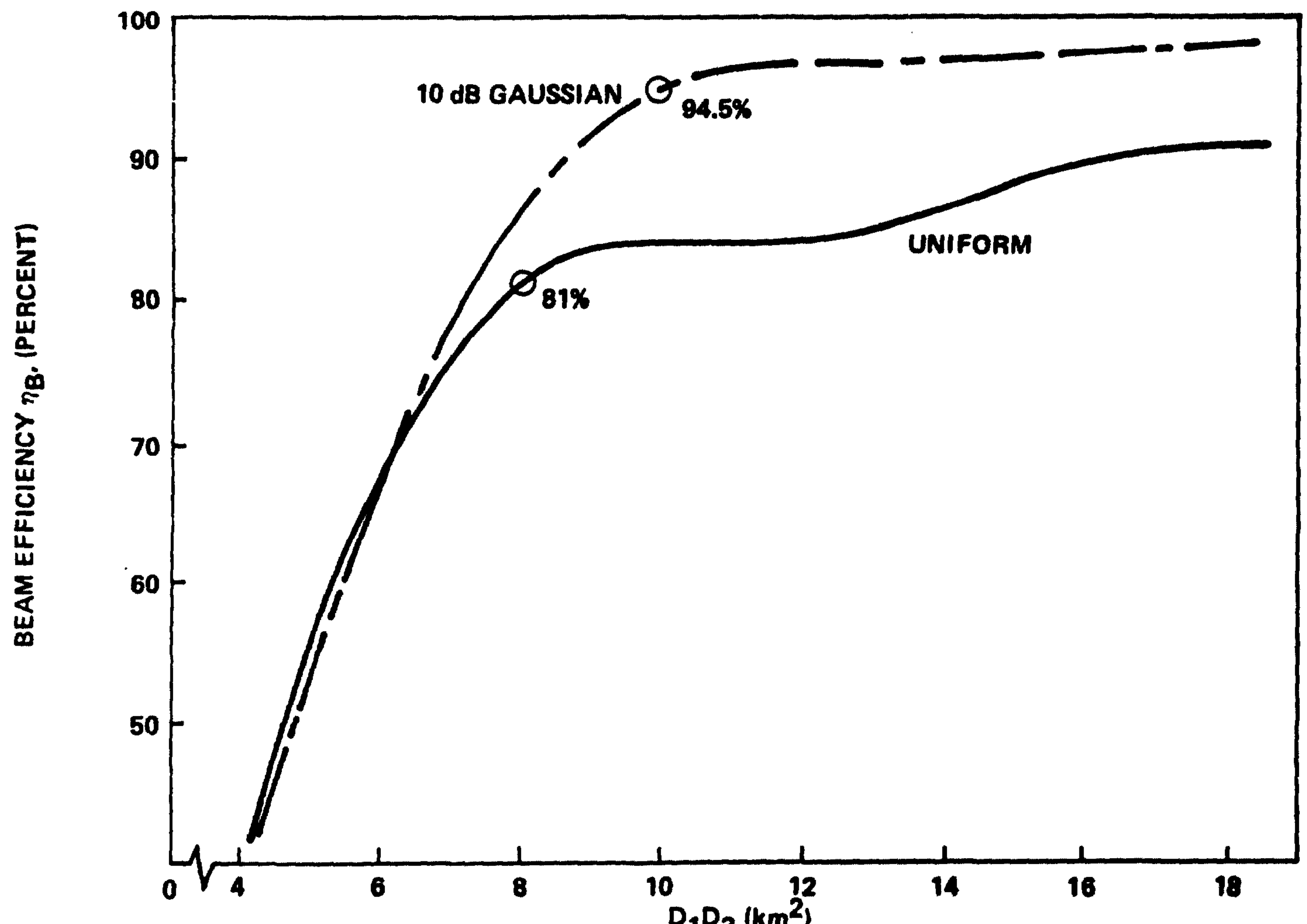
Note: SSPA effective radiating temperature = 125°C.

BEAM EFFICIENCY VERSUS SPACE ANTENNA-RECTENNA DIAMETER PRODUCT

In comparing the potential utility of the uniform illumination function as a means of increasing the power of a solid state SPS configuration with the Gaussian illumination, the curves below outline the achievable ideal antenna beam efficiency. The selected values of D_1 and D_2 are based on the rectenna size D_2 beyond which the return for increased efficiency is marginal. The uniform illumination in this case gives a value of 81% compared with 94.5% for the uniform distribution. Design curves for these cases were developed separately, yielding power output and space antenna dimensions as a function of thermal and ionospheric constraints.

Beam Efficiency η_B Versus Space Antenna Rectenna Diameter Product

SPS-2129

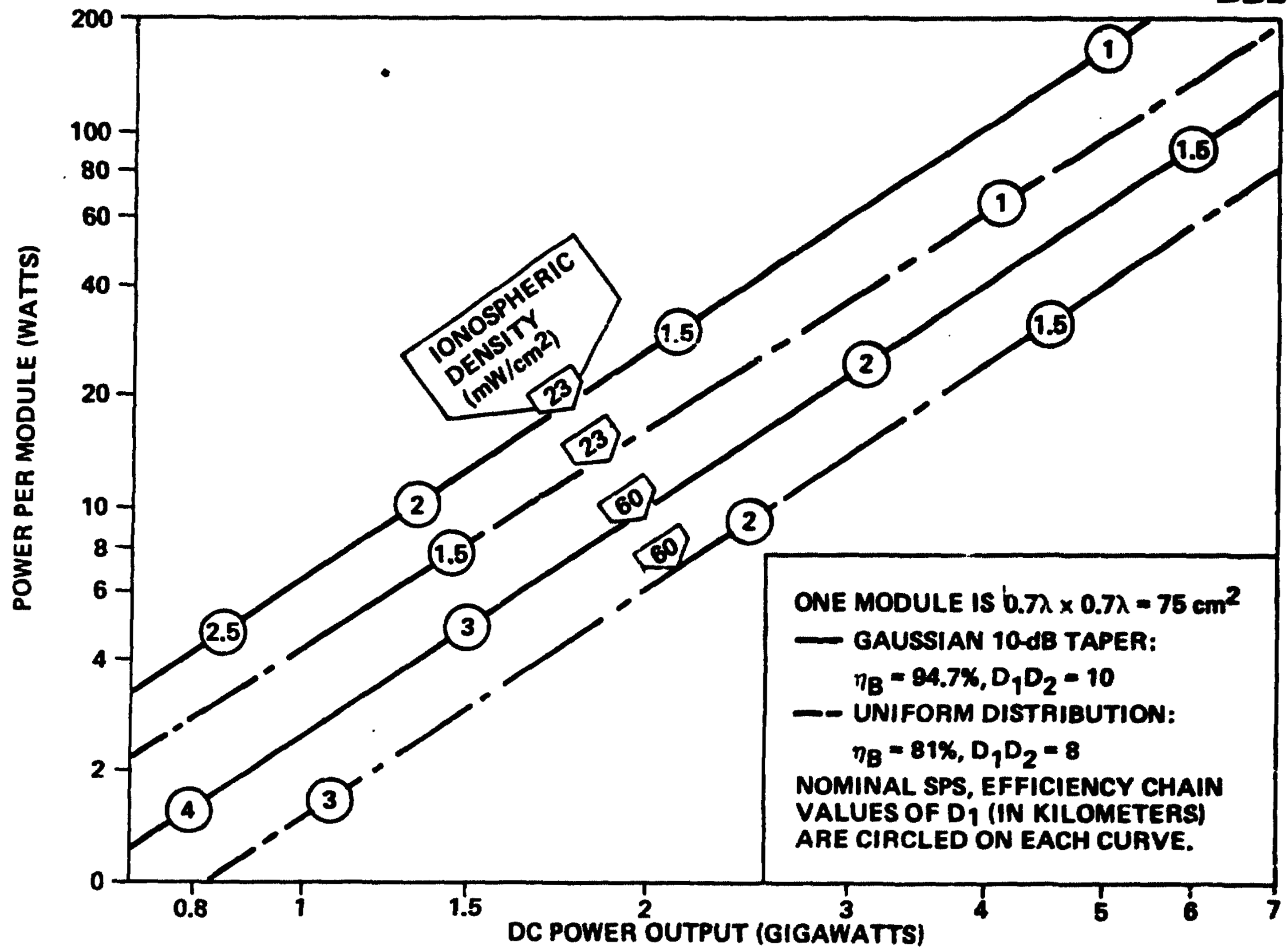


COMPARISON OF UNIFORM AND GAUSSION ILLUMINATION FUNCTION

A typical solid state SPS design might be considered as built up a number of modules, each corresponding to a 75 cm^2 cell, typical of dipole or slot spacing at 2.4 GHz. Taking 1 Kw/m^2 as a conservative thermal limit at 125^oC, with a design efficiency of 75%, one can derive an rf density $P_{rf} = (\frac{\eta}{1-\eta}) P_{th} = 3\ Kw/m^2$. This corresponds to 22.5 watts for a dipole cell. The derived curves in the attached figure indicate that such a design, if 10-20 individual devices of 1-2 watts each were configured in the module feeding one dipole, would result in 1.8 Gw output with 1.7 km space antenna dia. (10 db taper) or 2.2 Gw with a 1.3 km space antenna (uniform distribution).

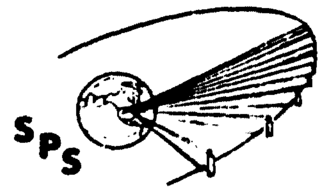
Comparison of Uniform and Gaussian Illumination Function

SPS 2135

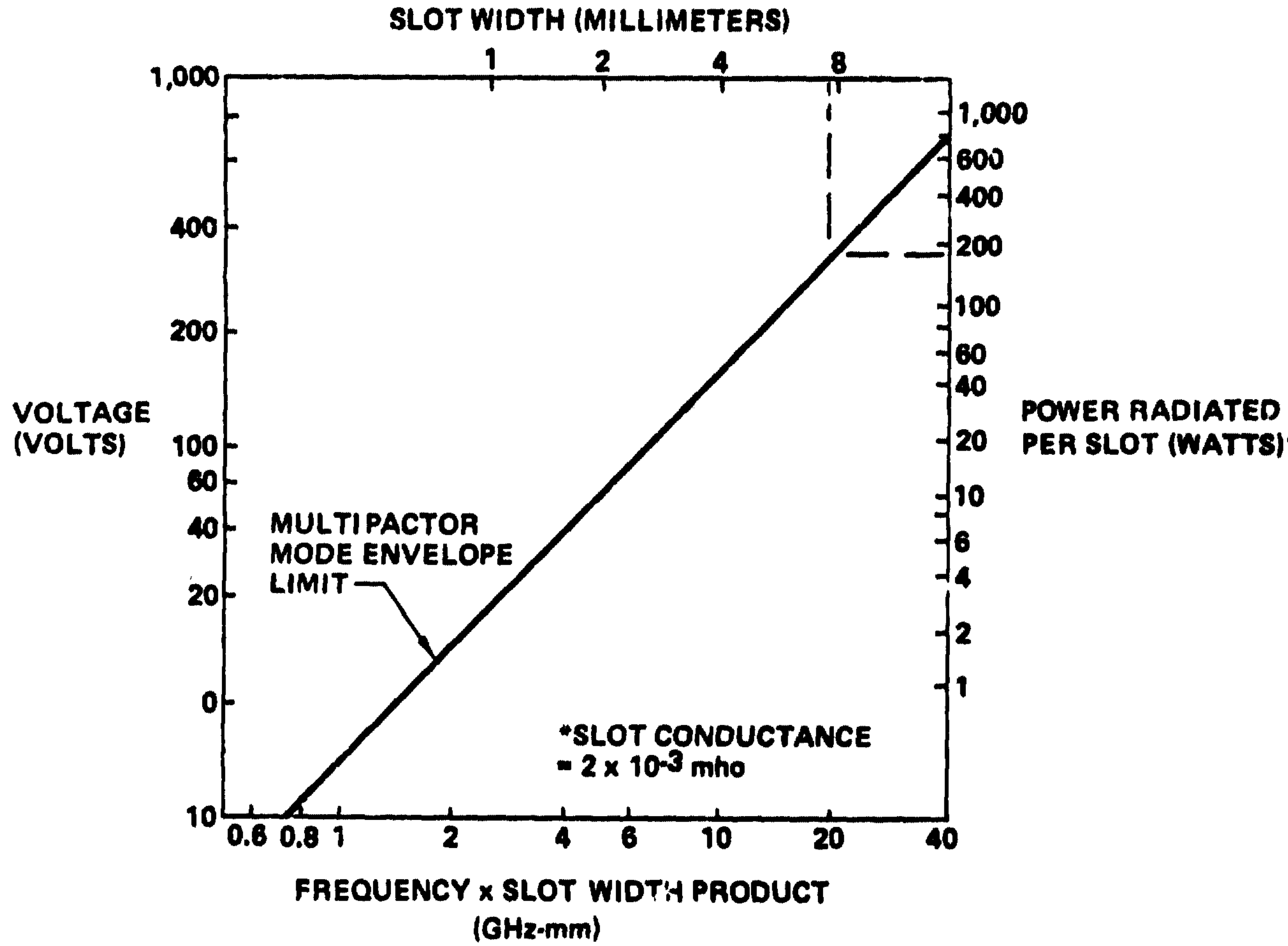


IMPACT OF MULTIPACTOR OF SPACE ANTENNA SLOT DESIGN

The baseline 5 GW SPS design, with an area of $\sim$60 cm^2 per slot and an rf loading of 23 kw/m^2 at the center, result in a power per slot of $\sim$140 watts. The conservative worst-case design criterian shown on this curve suggests that this should be accomplished with a slot width of 6-7 mm which is considered greater than desirable. Further work is required including the slot conductance, conflicting factors of 2 in the analysis, and practical spacecraft experience based on less stringent Fd products. Multipactor suppresion techniques also need to be investigated, such as coatings and dielectric inserts in slots.



Impact of Multipactor on Space Antenna Slot Design



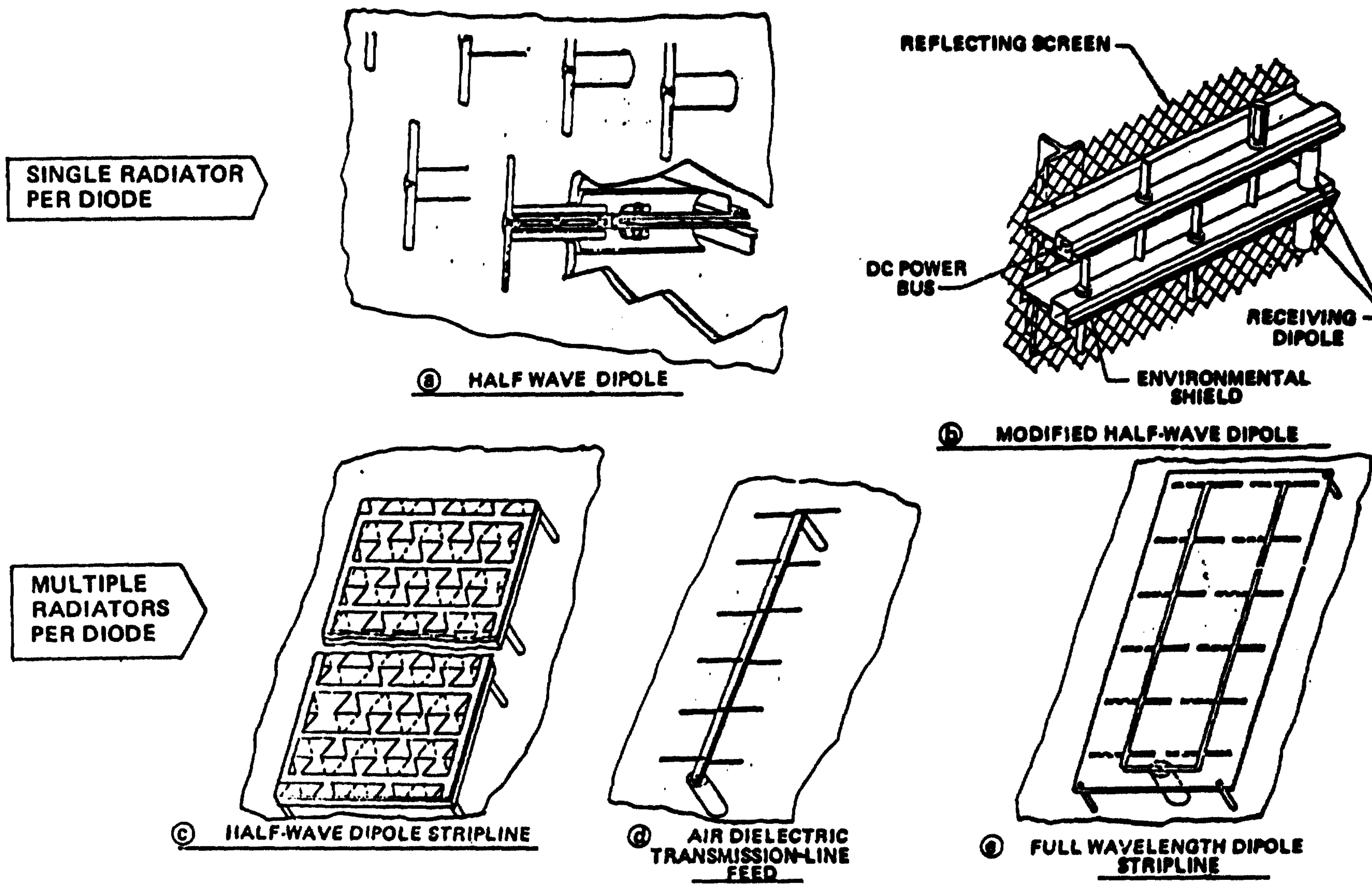
Rectenna Options

RECTENNA RECEIVING ELEMENT OPTIONS

In order to achieve efficient rectification, it may be necessary to connect several dipoles to a single rectifier, creating small areas of coherent reception. Several such options are shown including the $\lambda/2$ "Bowtie" dipole (c) and a full wavelength dipole, either in air dielectric (d) or in stripline (e). The full λ dipole may be easier to match to the rectifier because of its higher impedance. Also shown is a modified lumped element $\lambda/2$ dipole, designed for ease of automated manufacture by Raytheon (b). The originally tested dipole configuration for high rectification efficiency is shown in (a).

Rectenna Receiving Element Options

SPS-1764



POTENTIAL RECTENNA CONFIGURATIONS

Aside from connecting several dipoles coherently, it is possible to increase the collective energy density by concentration using the Hogline configuration (cylindrical parabola) shown in (B).

The figure shows possible configurations of the conventional flat rectenna and the Hogline, either ground located, or elevated for possible dual land use.

Potential Rectenna Configurations

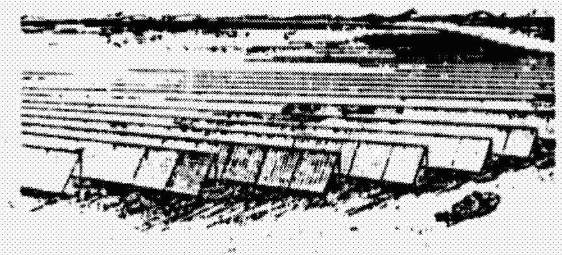
BOEING

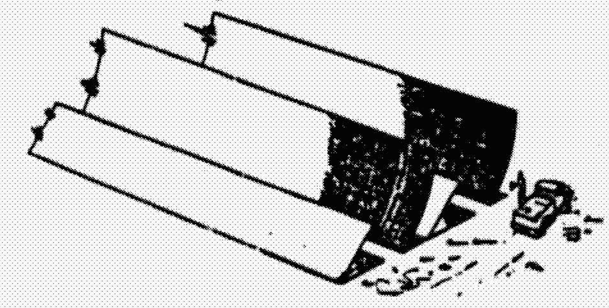
SPS-1765

NON-CONCENTRATING

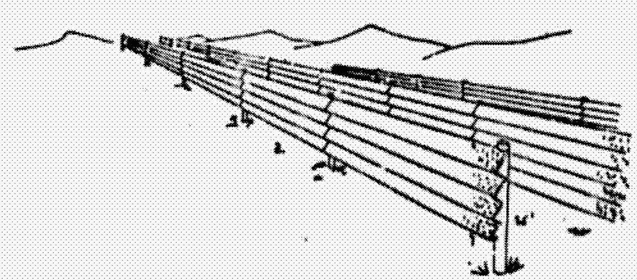
CONCENTRATING

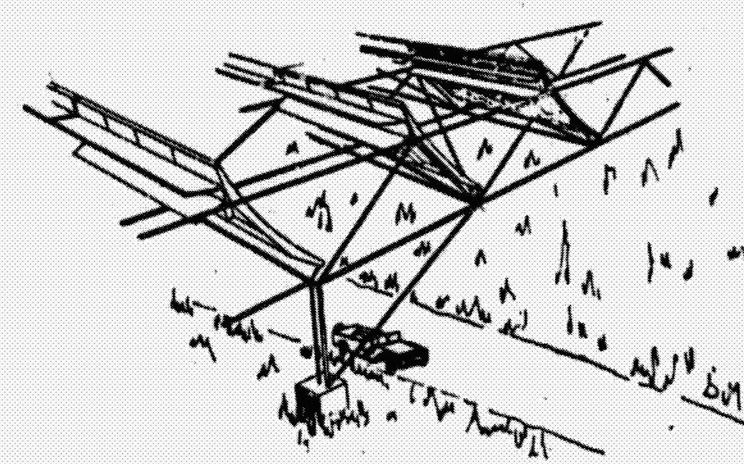
GROUND LOCATION





ELEVATED





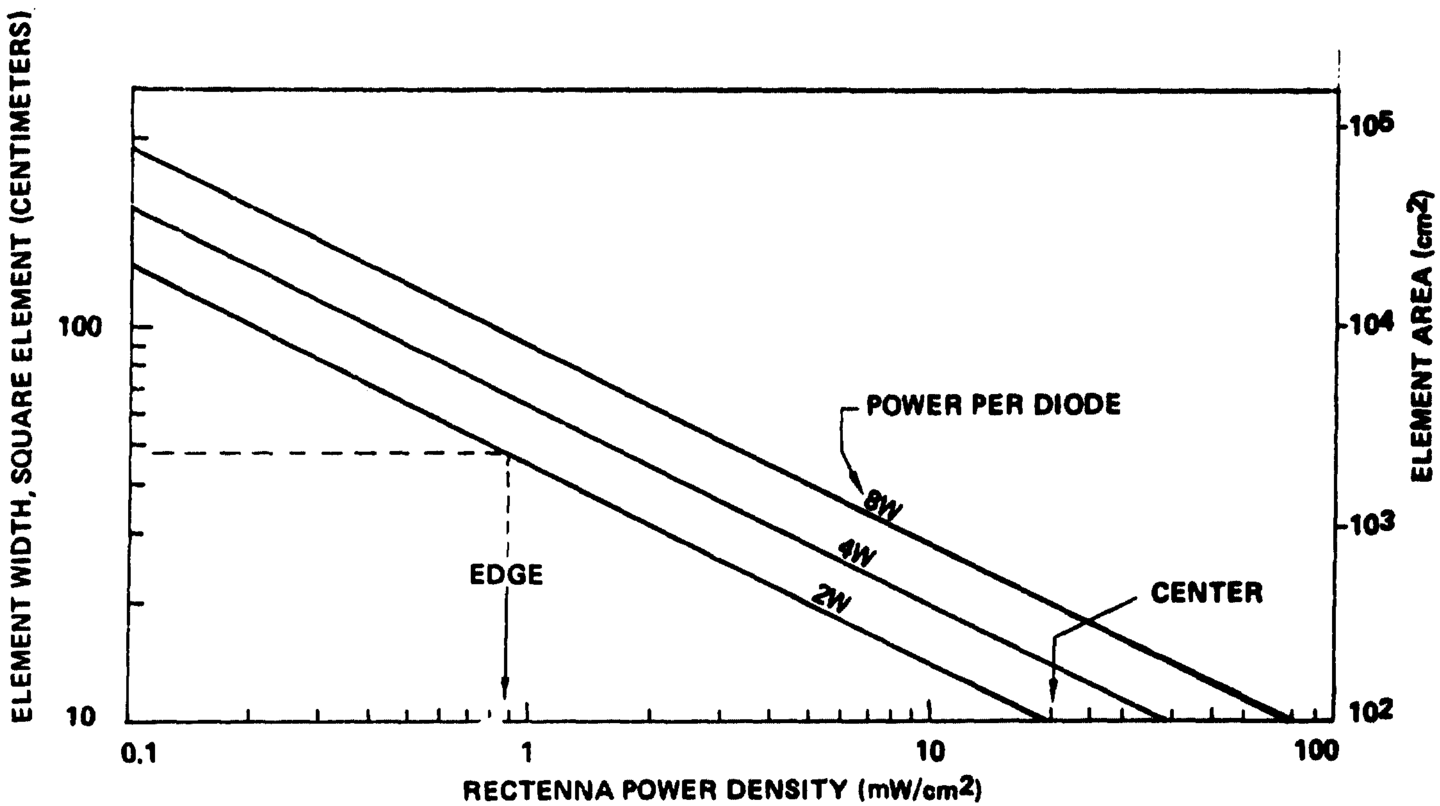
ⓐ FLAT RECTENNA

ⓑ CYLINDRICAL PARABOLA

REQUIRED RECTENNA ELEMENT SIZE FOR GIVEN INCIDENT POWER DENSITY

To achieve good rectification efficiency (~85%), it is desirable to develop 2-6 watts of rf power at each diode. This figure shows the rectenna element width and area required to achieve these values at the center and at the edge of the rectenna.

Required Rectenna Element Size for Given Incident Power Density



POTENTIAL RECTENNA CONFIGURATIONS FOR EFFICIENT RECTIFICATION

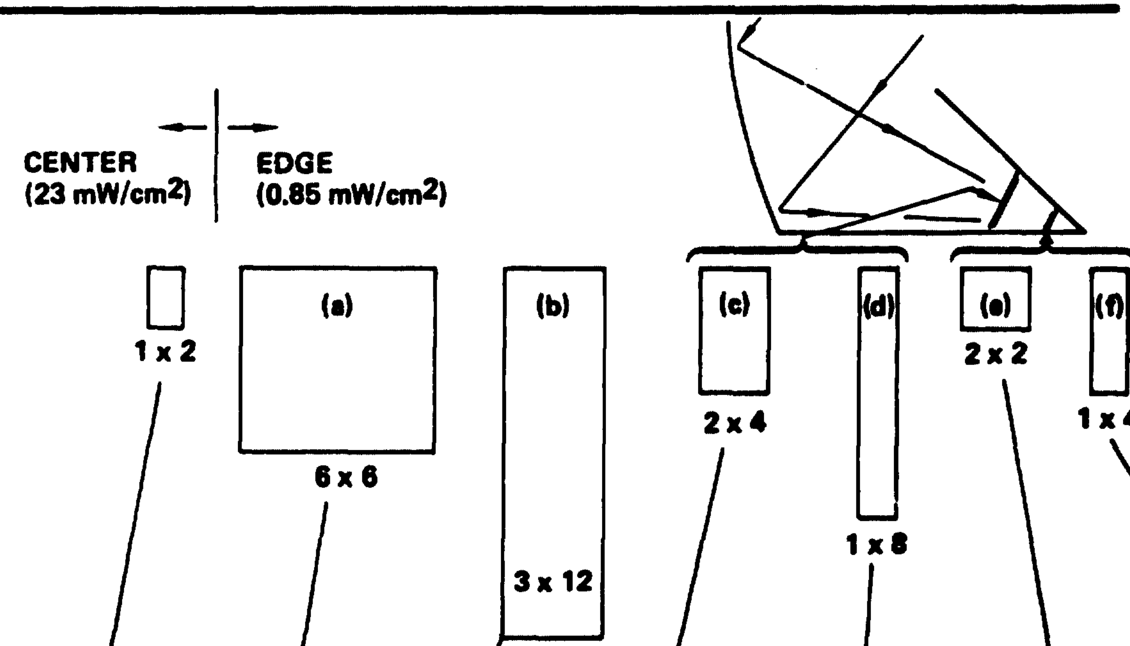
Good rectenna collection efficiency can easily be obtained at the center of the receiver (23 mw/cm^2), where with only two 75 cm^2 modules, a per-diode power of 3.45 watts can be developed. At the edge of the rectenna, however, methods of increasing diode power must be developed either by coherent interconnection of dipoles (Case (a) and (b), optical concentration, or combination of both (c,d,e,g).

For a given assumed satellite position accuracy, the loss due to gain reduction has been estimated from previous curves for several possible layouts at the rectenna edge. Additive losses in the two dimensions can be minimized by matching the rectenna length-to-width ratios to the relative angular position accuracies available in the satellite plane. For example (Case c), with modest optical concentration (4:1) and relatively few dipoles per panel (8 for 75 cm^2 dipole cell size), the loss for a $.5^o \times .1^o$ orbit position stability is less than 1%.

Potential Rectenna Configurations for Efficient Rectification

SPS-2131

BOEING



		1 x 2	(a) 6 x 6	(b) 3 x 12	(c) 2 x 4	(d) 1 x 8	(e) 2 x 2	(f) 1 x 4
NUMBER OF MODULES (75 cm^2 EACH)		2	36	36	8	8	4	4
PANEL SIZE, m	w_x	0.087	0.52	0.26	0.17	0.087	0.17	0.087
	w_y	0.17	0.52	1.04	0.35	0.7	0.17	0.35
AREA, m^2	A	0.015	0.27	0.27	0.06	0.06	0.03	0.03
POWER PER DIODE	P	3.45	2.3	2.3	2.04	2.04	2.04	2.04
OPTICAL CONCENTRATION		NO	NO	NO	4:1	4:1	8:1	8:1
MATCHING LOSSES		LOW	HIGH	HIGH	MED	MED	LOW	LOW
LOSS FOR ORBIT STABILITY OF 0.5 deg x 0.1 deg	L_x	0	0.4%	0.1%	0.7%	0.7%	1.6%	1.6%
	L_y	0	0	0.1%	0.2%	0.8%	0	0.2%
	TOTAL	0	0.4%	0.2%	0.9%	1.5%	1.6%	1.8%

CAPTURE AREA OF DIFFERENT TYPES OF RECTENNA ELEMENTS

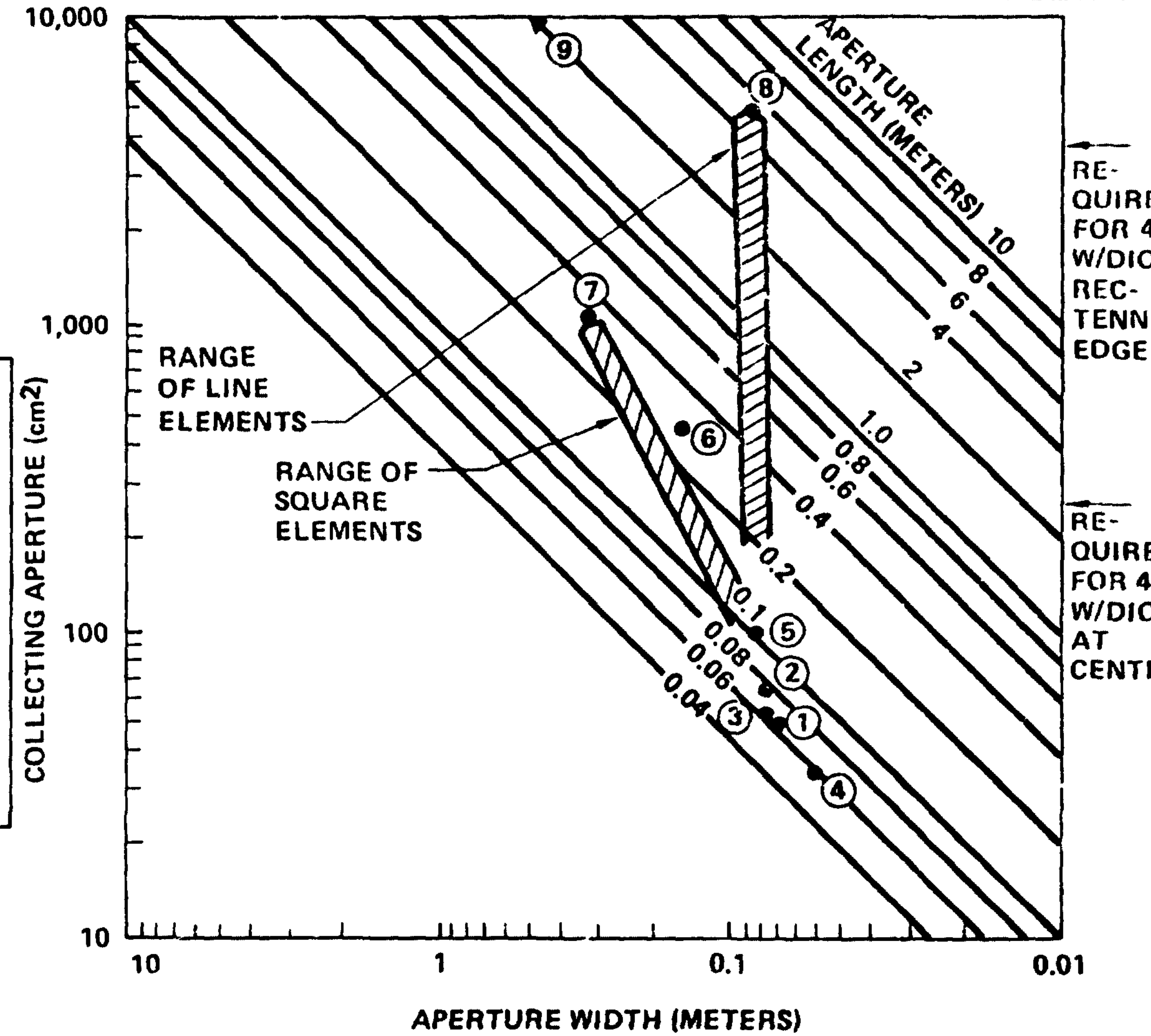
The choice of rectenna element is dictated by simplicity, ease of mass manufacture, element gain (i.e., collection area) and ease of matching to the rectifier. The non-coherent collection with one dipole is illustrated in cases (1) to (5) in the facing figure. The largest collection area per dipole results in the lowest total number of dipoles. The resonant cavity (6) and (9) and waveguide stick (8), represent larger coherent collection areas imposing increasingly greater requirements on the satellite position accuracy.

The Yagi antenna, shown for the case of a power gain of ∿100 (max. practical limit), would result in a minimum number of single elements (non-coherent), but represent complex manufacturing problems. Point (1) represents the baseline design dipole.

Capture Area of Different Types of Rectenna Elements

BOEING

SPS-2134

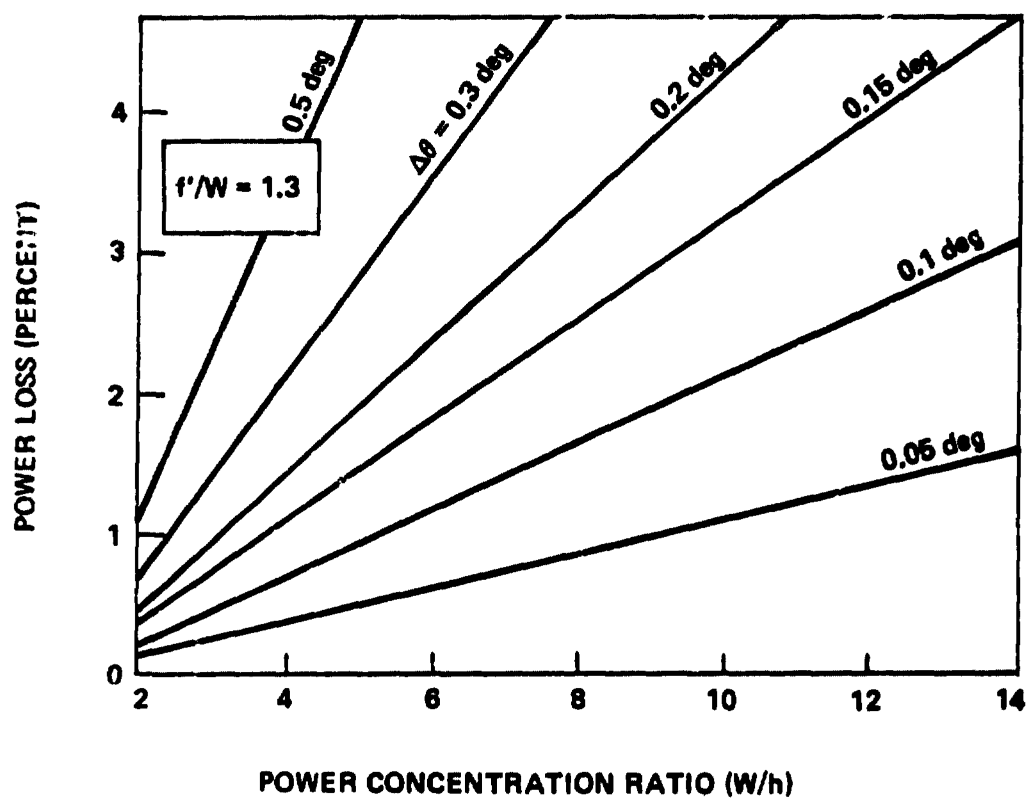


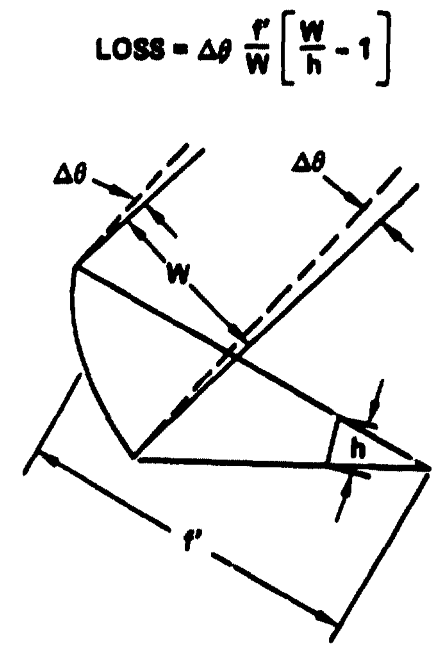
LEGEND:
1. BASELINE DIPOLE CELL ($\lambda/2$)
2. DIPOLE IN AIR DIELECTRIC (λ)
3. DIPOLE IN STRIPLINE (λ)
4. DIPOLE IN STRIPLINE ($\lambda/2$)
5. POTENTIAL DIPOLE CELL LIMIT
6. RECTENNA CAVITY ELEMENT (2 x 3 SLOTS, TYPICAL)
7. LIMIT OF YAGI ELEMENT
8. MAXIMUM WAVEGUIDE STICK LENGTH (30g)
9. TYPICAL CAVITY RADIATOR (ROCKWELL)

HOGLINE POINTING LOSSES VERSUS POWER CONCENTRATION RATIO AND SATELLITE POSITION ERROR

If optical concentration is used, such as with the Hogline rectenna configuration, the sensitivity to satellite position is increased, unless a method can be devised whereby a section of a rectenna can be activated if illuminated by rf. For a typical range of concentration ratio, this loss is indicated below. High concentration ratios are incompatible with tolerable losses unless the above suggestion can be implemented.

Hogline Pointing Losses Versus Power Concentration Ratio and Satellite Position Error



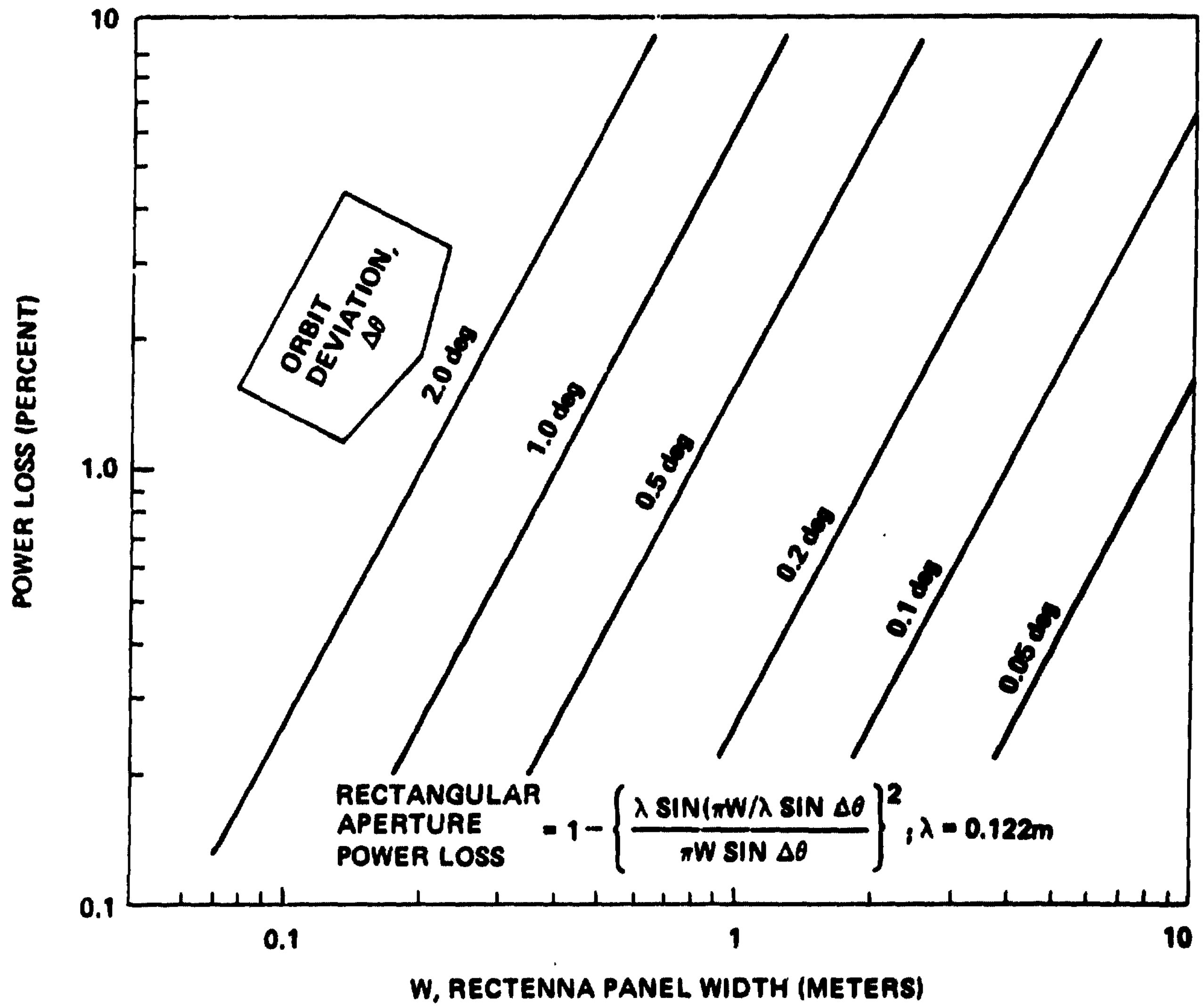


POWER LOSS DUE TO SPS ORBIT DEVIATION

For the case of coherent collection over a specified rectenna panel size, suggested for the case of parallelling a number of diodes per rectifier, the loss of gain due to either panel tilt or satellite angular displacement from the normal to the panel is indicated in the figure. For example, for a 1/2 meter panel width, the loss associated with gain reduction is less than 0.4% for a $1/2^{o}$ angular deviation.

Power Loss Due to SPS Orbit Deviation

SPS-2133



Construction and Operations

SATELLITE CONSTRUCTION AND OPERATION OVERVIEW

The satellite construction effort is divided into four major blocks of work. Alternate construction concepts will be analyzed and compared with the baseline that was established through Part III of the SPS study. If possible, by the midterm, a concept will be selected at which time further refinement in terms of base size and sensitivity to modular size will be performed as well as further work on antenna construction. More detailed construction and operations analysis will be performed on the selected concept during Phase 2. Initially, detailed operations associated with the LEO Construction Base and its design will be performed followed by similar operations associated with GEO Construction Base. Also occurring in Phase 2 will be the analysis associated with mission contol systems and operations, space transportation operations, maintenance systems and operations and finally an integrated operations plan will be developed.

Satellite Construction Overview

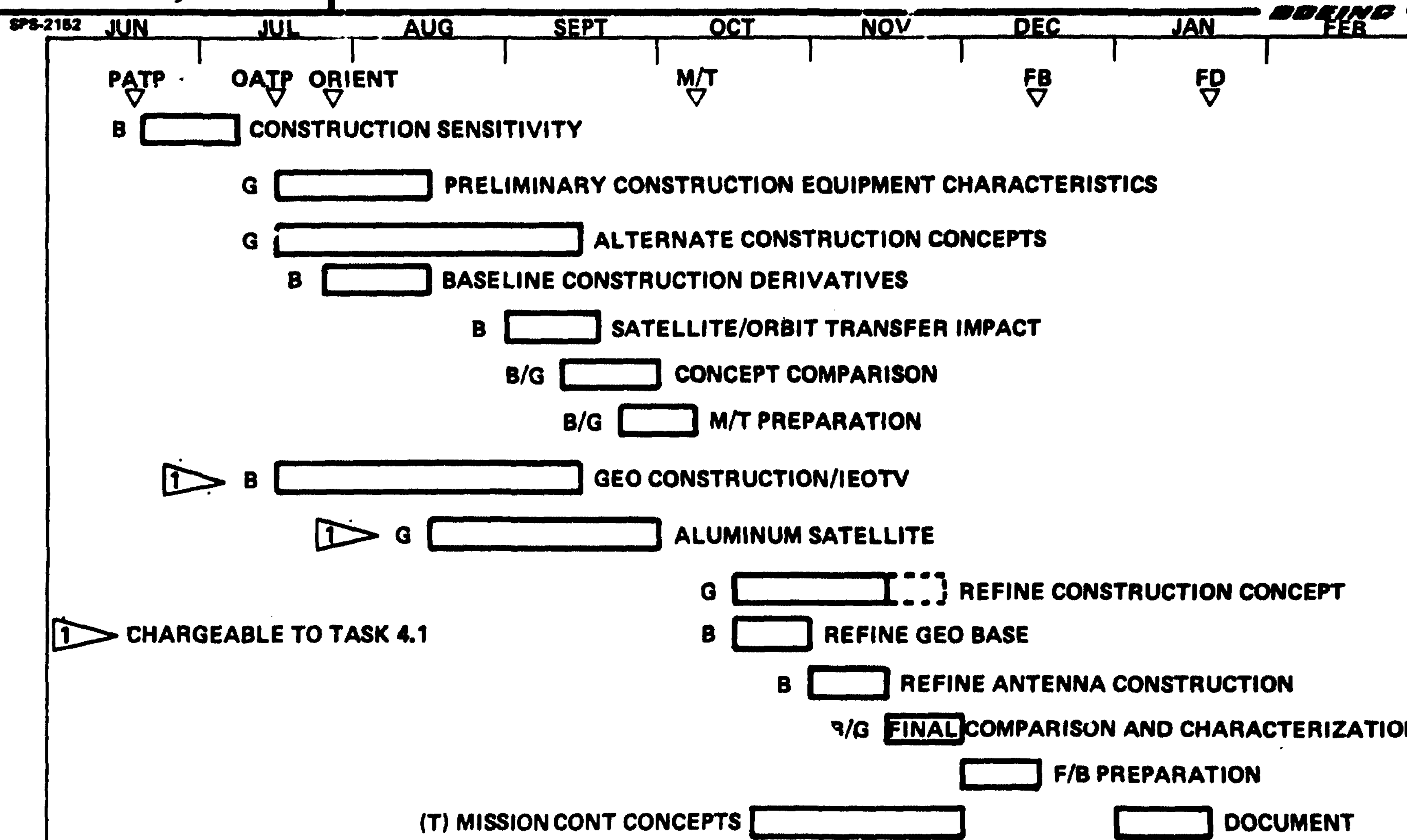
PHASE 1			PHASE 2		
0	3½+	6	7	11	15
ATP	MB	FB	ATP	MB	FB

ALTERNATE CONSTRUCTION CONCEPTS	CONCEPT REFINEMENT	LEO CONSTRUCTION BASE AND OPERATIONS	GEO CONSTRUCTION BASE AND OPERATIONS

PHASE 1 CONSTRUCTION AND OPERATIONS SCHEDULES

A more detailed indication of the tasks and schedules associated with Phase 1 is presented. By midterm, alternate construction concepts will have been analyzed. Included in these concepts will be that of a GEO construction concept using independent electric orbit transfer vehicles for transfer of cargo from low earth orbit to geosynchronous orbit. Selection of a preferred construction concept will be performed by the midterm. The selected concept will then be refined up through the final portion of Phase 1. Refinement of the size of the GEO base and construction operations associated with the antenna will also be performed during Phase 1. A preliminary indication of mission control concepts will also be performed.

Phase 1 Construction and Operations Schedules

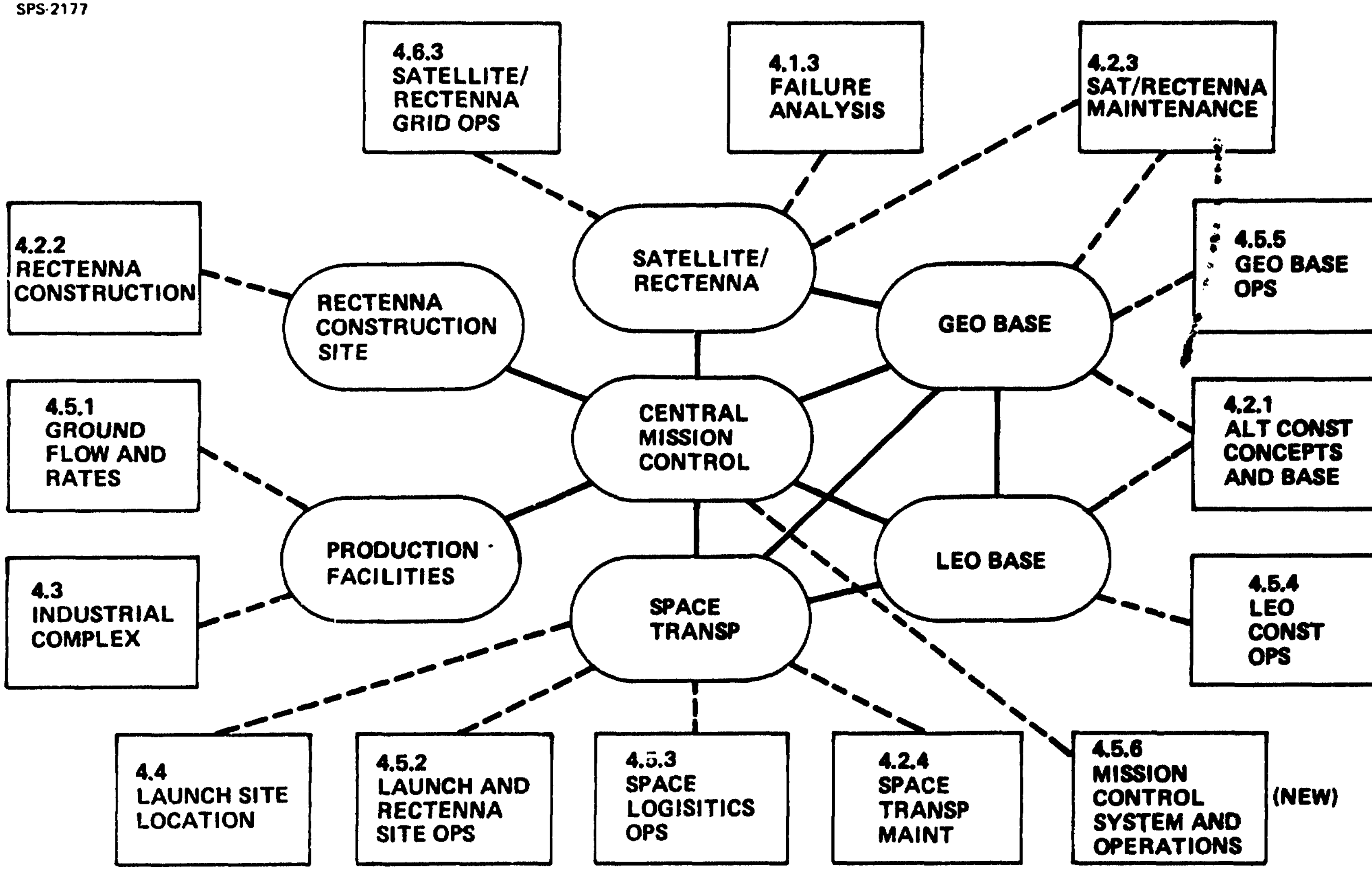


MISSION CONTROL INT FACES

A new subtask proposed for Task 4.5 is called Mission Control System and Operations. The interfaces between the program elements (oval boxes) as well as that associated with the various tasks (rectangular boxes) of the study are indicated. During Phase 1, mission control system and operations work will be confined to analyzing the options that are available in terms of the division of the responsibility between the major program elements and making a selection. An example of this work would be establishing which program element would control the flight of an orbit transfer vehicle with the options being from central mission control, a LEO construction base, a GEO construction base, or through some other manner. During Phase 2, the physical interfaces will be defined between the program elements followed by resource requirements for each of the control centers in terms of manpower and computation capability. Another subtask proposed for Task 4.5 will be that of the integrated mission operations plan-where all operations defined in other sections of the study will be summarized to give a concise end-to-end operations description.

Mission Control Interfaces

SPS-2177

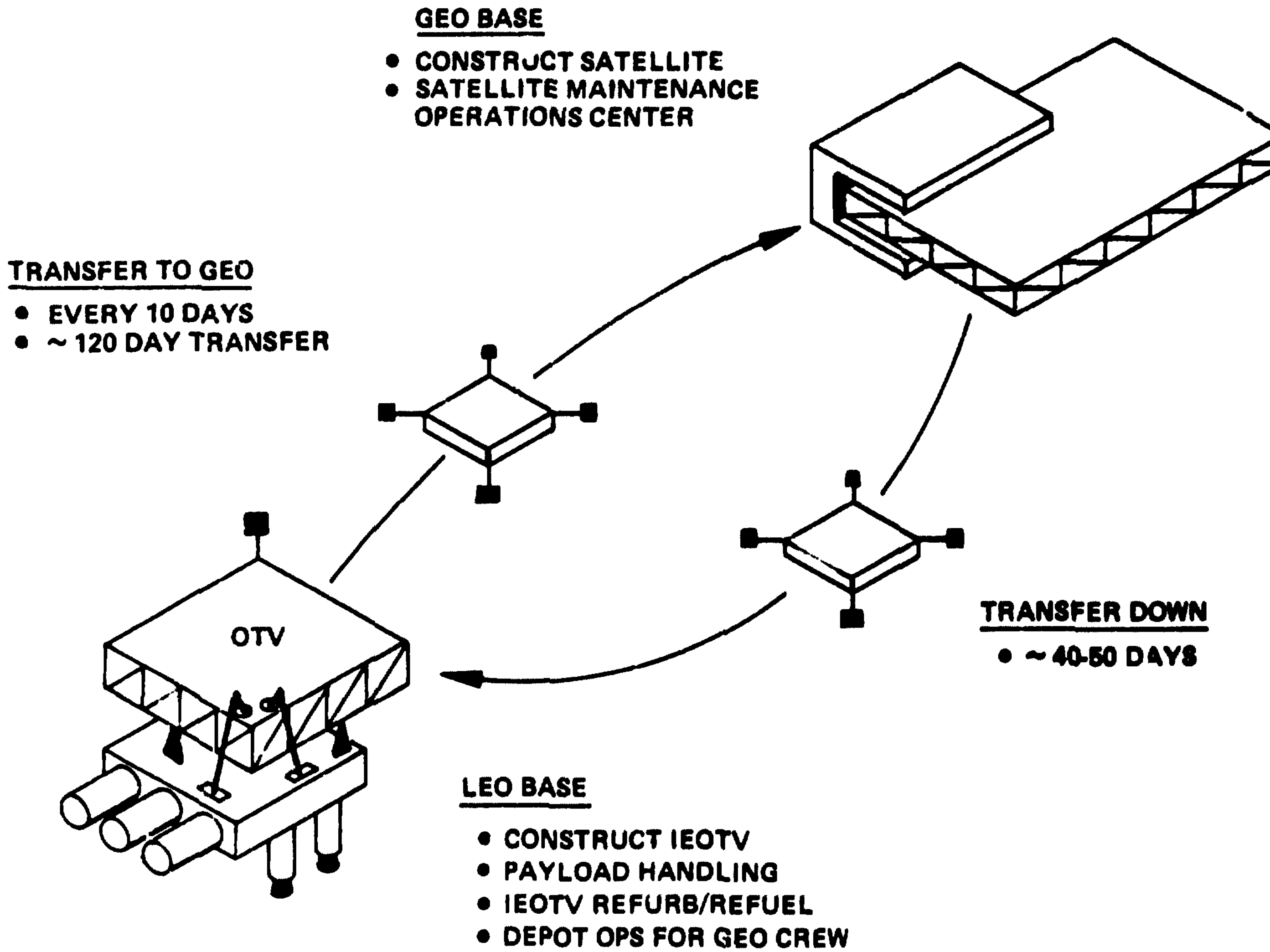


GEO Construction With Independent Electric Orbit Transfer Vehicle (IEOTV)

GEO CONSTRUCTION/ELECTRIC OTV CONCEPT

As a means of establishing the framework for discussing this concept, an overall illustration of the concept is presented. Initially, a low earth orbit base is established with its initial operations being that of constructing the electric orbit transfer vehicles. Following construction the EOTV's are then used to transport components of the satellite up to a GEO construction base where they will be assembled into a monolithic 5 GWE satellite. Following delivery of the components, the electric orbit transfer vehicles will be returned to the low earth orbit base where they will be refurbished, refueled and reloaded with additional components and repeat the delivery operations. The concept offers the benefits of the high performance associated with the LEO construction/self-power concept and the monolithic construction operations associated with the GEO construction approach. Cost effectiveness of this concept, however, will be dependent upon several factors which at present have little data base; namely, that of the degree of reusability of the electric orbit transfer vehicle and the design life associated with its components.

GEO Construction/Electric OTV Concept



EMPHASIS AREAS

Emphasis Areas to be addressed in analyzing the GEO construction/IEOTV concept are indicated. In vehicle sizing and performance, both silicon and gallium arsenide cells will be considered. The principle effort here will be establishing a cost optimum specific impulse and trip time as well as basic vehicle sizing parameters. These sizing parameters will be used in establishing the vehicle configuration which in turn will be used to perform the construction analysis of the electric OTV's. All phases of mission operations will be analyzed with particular emphasis given to the reusability aspect of the electric OTV. The key issue associated with vehicle construction will be how fast the fleet is to constructed. The LEO construction base definition will not only include the systems and personnel associated with construction of the electric OTV, but also must serve as maintenance base for the OTV as well as provide depot operations associated with supporting crew and supply deliveries to the GEO base. The satellite construction impact analysis will primarily deal with the modifications in the construction operation when one is constructing a monolithic satellite as compared with a modular satellite. The launch operations impact will consider the benefits to the concept if launch is made from a lower latitude. Cost analysis of the concept will emphasize initial investment cost and dollars per delivered kilogram of satellite.

Emphasis Areas

- ✓ VEHICLE SIZING/PERFORMANCE
- ✓ CONFIGURATIONS
- ✓ MISSION OPERATIONS
  - REUSABILITY
- VEHICLE CONSTRUCTION OPERATIONS
- LEO BASE DEFINITION
- SATELLITE CONSTRUCTION IMPACT
- LAUNCH OPERATIONS IMPACT
- ✓ COST

✓ TO BE DISCUSSED

VEHICLE SIZING AND PERFORMANCE

The payload delivered requirement of 4,000 metric tons per flight relates to the transfer of 10 HLLV payloads. The down payload requirement of 400 metric tons assumes no repackaging of the payload will be done at the LEO base and, therefore, the payload rack and containers for the components must be delivered to GEO as well as returned to LEO for reuse. Previous analysis has assumed the rack and containers to be 10% of the gross payload. The GEO construction concept shows a greater mass delivered to GEO than that associated with LEO construction since the value includes 96,000 metric tons associated with the satellite plus an additional 10,000 metric tons associated with the payload rack and containers as previously discussed. The variables in this analysis will be that associated with selecting the cost optimum specific impulse and trip time. Specific impulse primarily affects the propellant loadings and the size of the power generation system, with propellant loadings primarily influencing the operations cost while the vehicle size will impact the initial investment and amortized cost. Trip time will influence the initial investment cost.

Vehicle Sizing and Performance

- PAYLOAD REQUIREMENTS
  - PER FLIGHT
    - UP — 4,000 MT
    - DOWN — 400 MT
  - PER SATELLITE

	GEO CONSTRUCTION	LEO CONSTRUCTION
• UP	106,000 MT	100,000 MT
• DOWN	10,000 MT	NONE

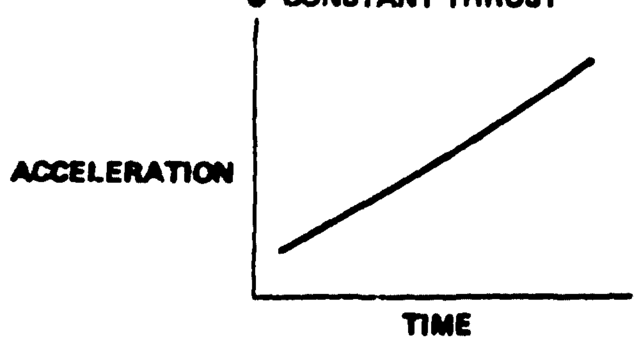
- KEY VARIABLES
  - SPECIFIC IMPULSE
    - HIGH I_S — LESS PROPELLANT, BIGGER ARRAY
    - LOW I_S — MORE PROPELLANT, SMALLER ARRAY
  - TRIP TIME
    - SHORT — BIG ARRAY, FEW VEHICLES
    - LONG — SMALL ARRAY, MORE VEHICLES

TRANSFER ACCELERATION CAPABILITY

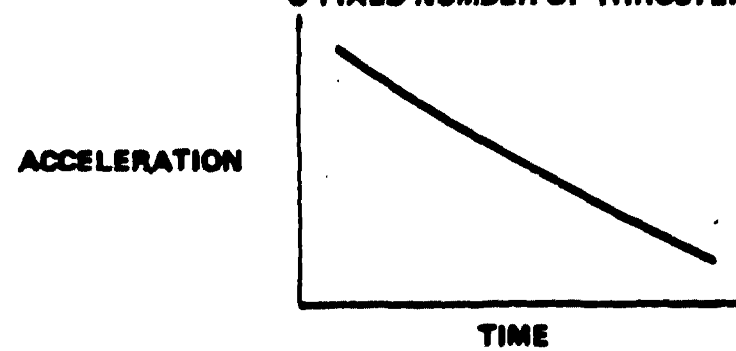
Several contrasting parameters dealing with acceleration are present in analyzing low acceleration, solar powered, transportation systems. System mass decreases with time and as a result provides an increase in acceleration with a constant thrust level. Correspondingly, as time goes by, the power output from the solar arrays will be decreasing due to degradation after passing through the Van Allen belts and accordingly, the acceleration will be going down. An estimate of the degradation for several trip times is indicated. Fast trip times require more power, however, the average available power will be higher since the vehicle will be passing through the Van Allen belts in a shorter period of time. For example, a 120 days transfer time between LEO and GEO, will have an average power output approximately 86% of that at the beginning of the mission.

Transfer Acceleration Capability

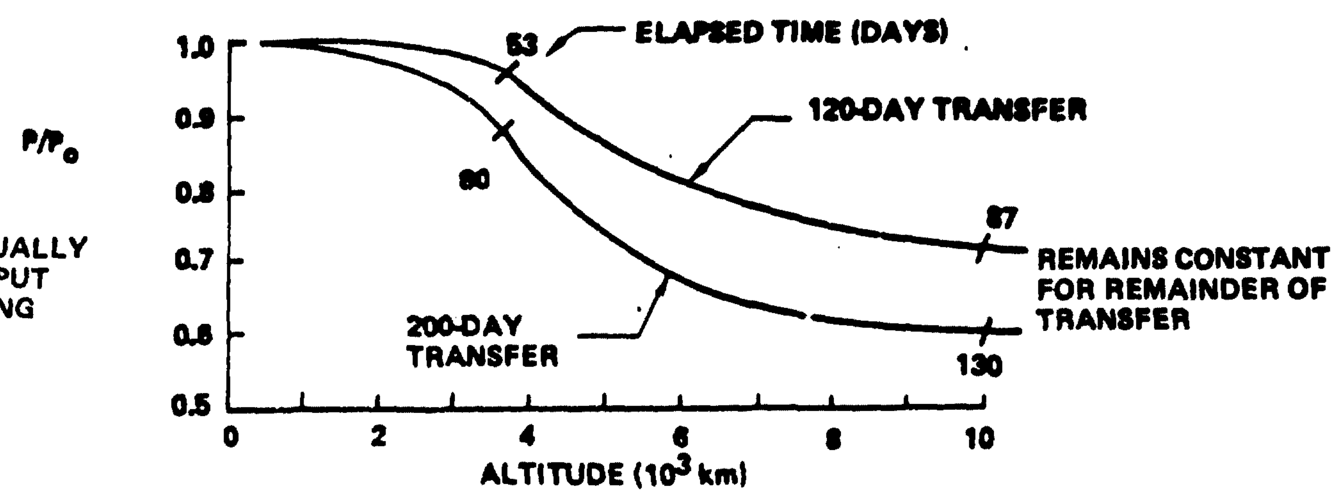
MASS
- DECREASING
- CONSTANT THRUST



ARRAY POWER
- DECREASING
- FIXED NUMBER OF THRUSTERS



NOTE: ARRAY WILL ACTUALLY HAVE MORE INITIAL OUTPUT THAN P DUE TO ANNEALING RECOVERY LIMITS.

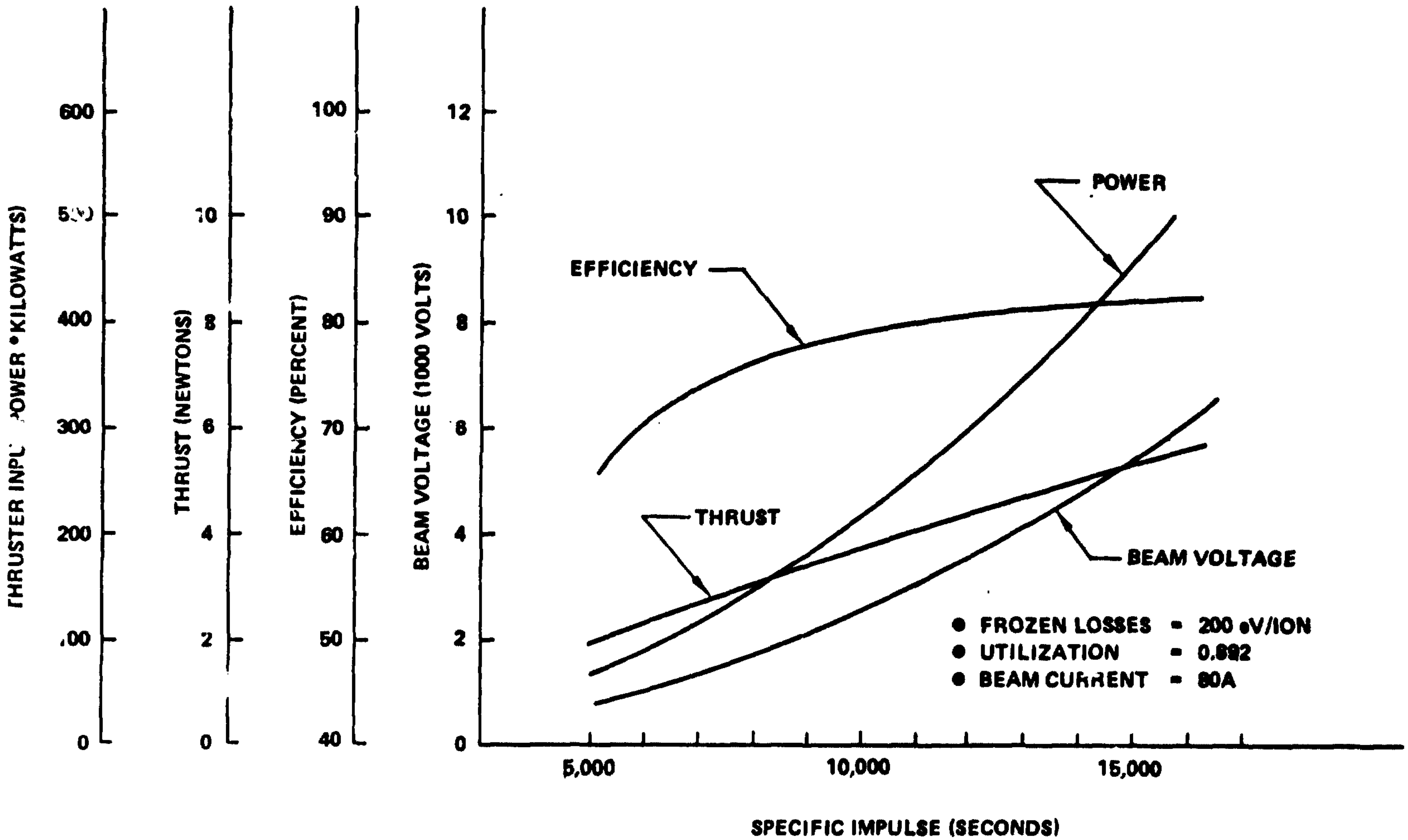


120 CENTIMETER ARGON ION THRUSTER PERFORMANCE

Another key parameter in establishing system level performance is the performance obtained from the ion thrusters. The characteristics indicated are the same as those used for the self-power analysis performed during the past SPS study. These characteristics are based on a beam current of 80 amps which is well within the projected growth capability from present day thrusters. The beam current affects the thrust level and power characteristics and also is a key factor in establishing the life characteristics associated with the thruster. Component life is inversely proportional to beam current and power density and with 80 amps is expected to be 8000 hours for the grids and cathodes.

120-CM Argon Ion Thruster Performance

SPS-571

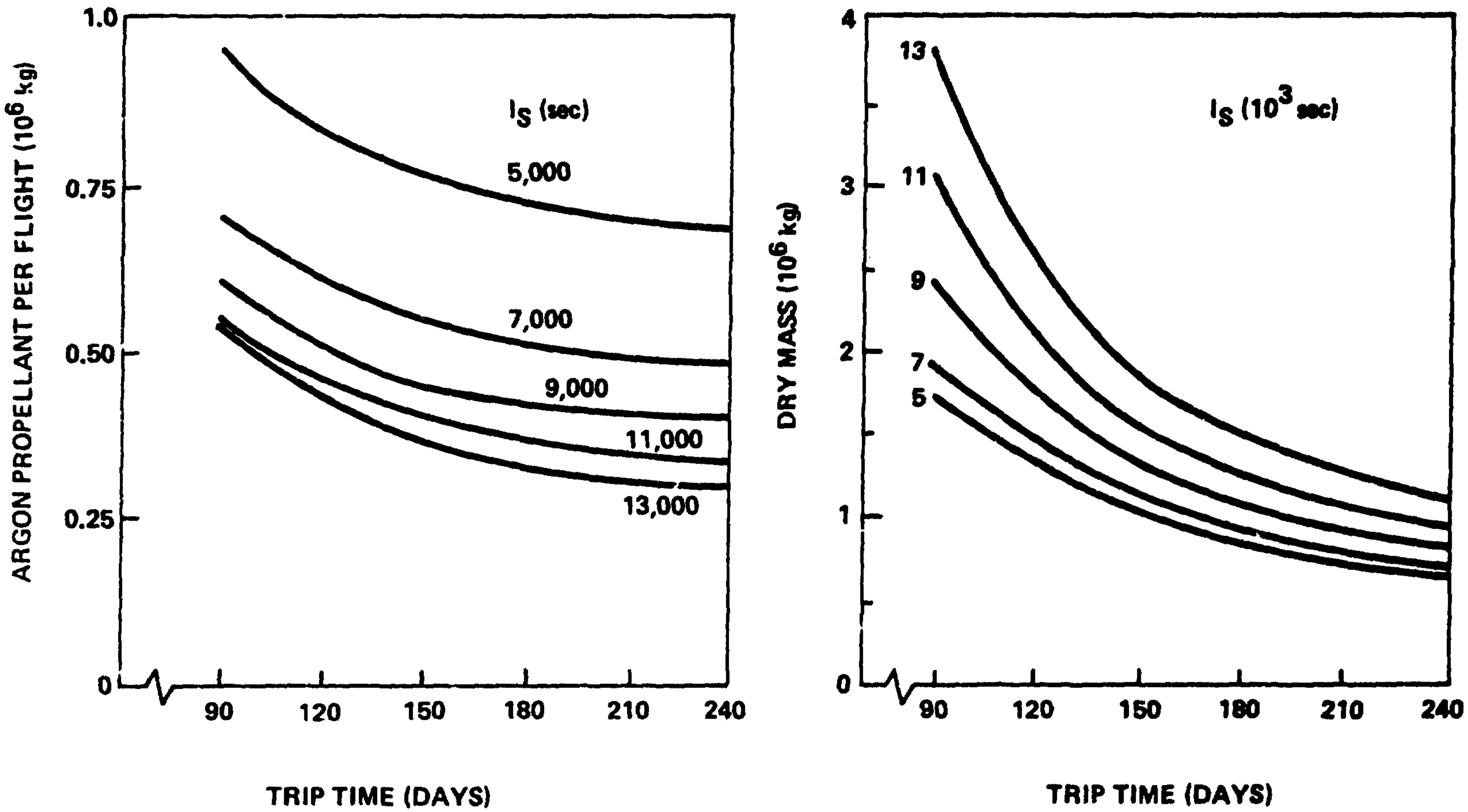


PRELIMINARY IEOTV PERFORMANCE

The impact of various specific impulses and trip times on propellant loading and dry mass of a vehicle is indicated. Lower propellant loading occur with higher specific impulses and longer trip times, with the latter occurring due to the vehicle having a lower dry mass since less power is required with long trip time. Power requirements are shown on the following chart.

Preliminary IEOTV Performance

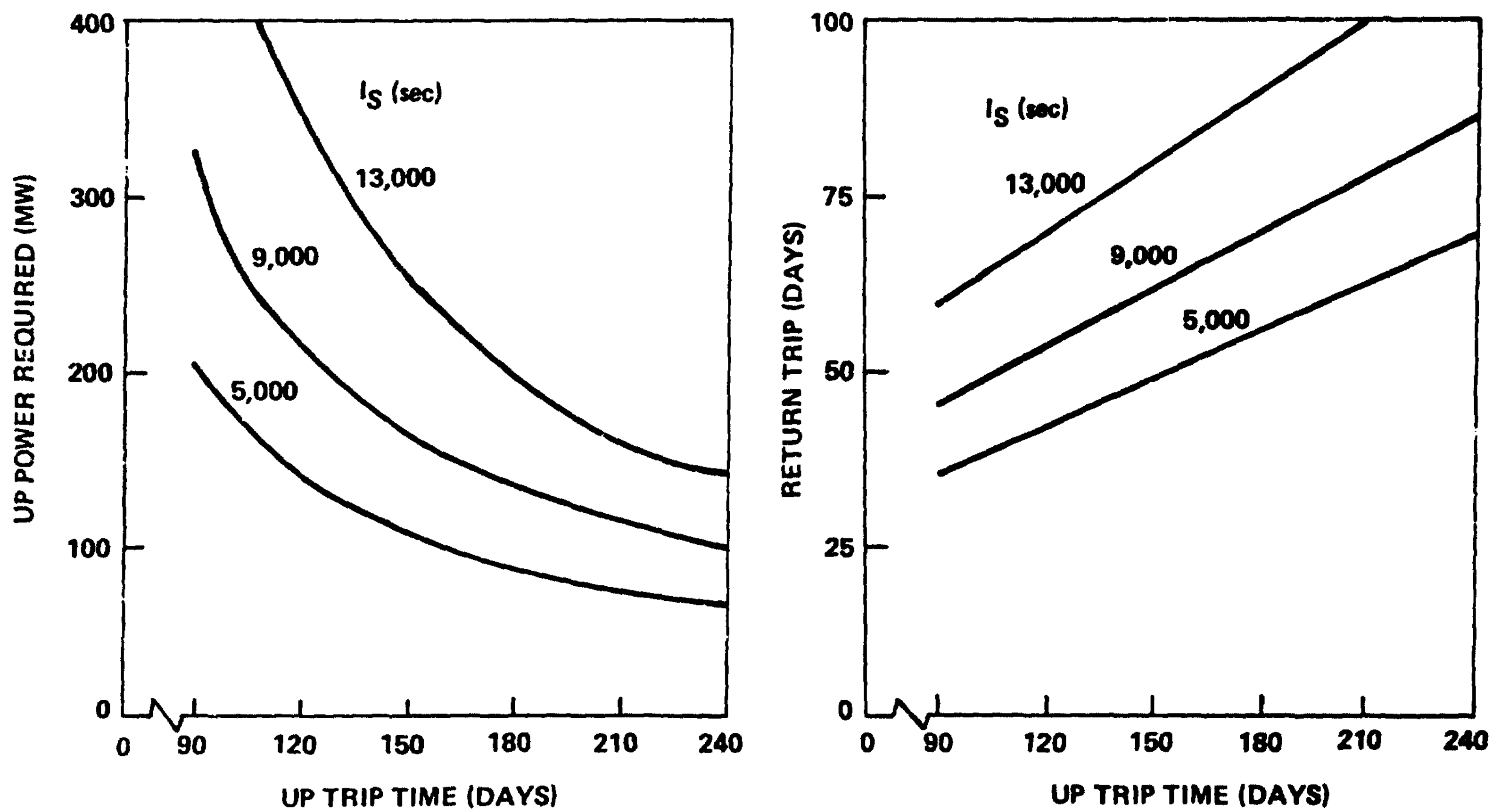
SILICON SOLAR CELLS



PRELIMINARY TRANSFER CHARACTERISTICS

Two other key parameters associated with various trip times and specific impulse are the power required for the transfer and the return trip time. Power requirement is significant in terms of sizing the basic vehicle while the return time is important to overall fleet sizing due to its impact on total turn around time for a given vehicle. For a given up trip time, vehicles having a lower specific impulse have shorter return trips due to having lower dry mass as was indicated on the preceding chart.

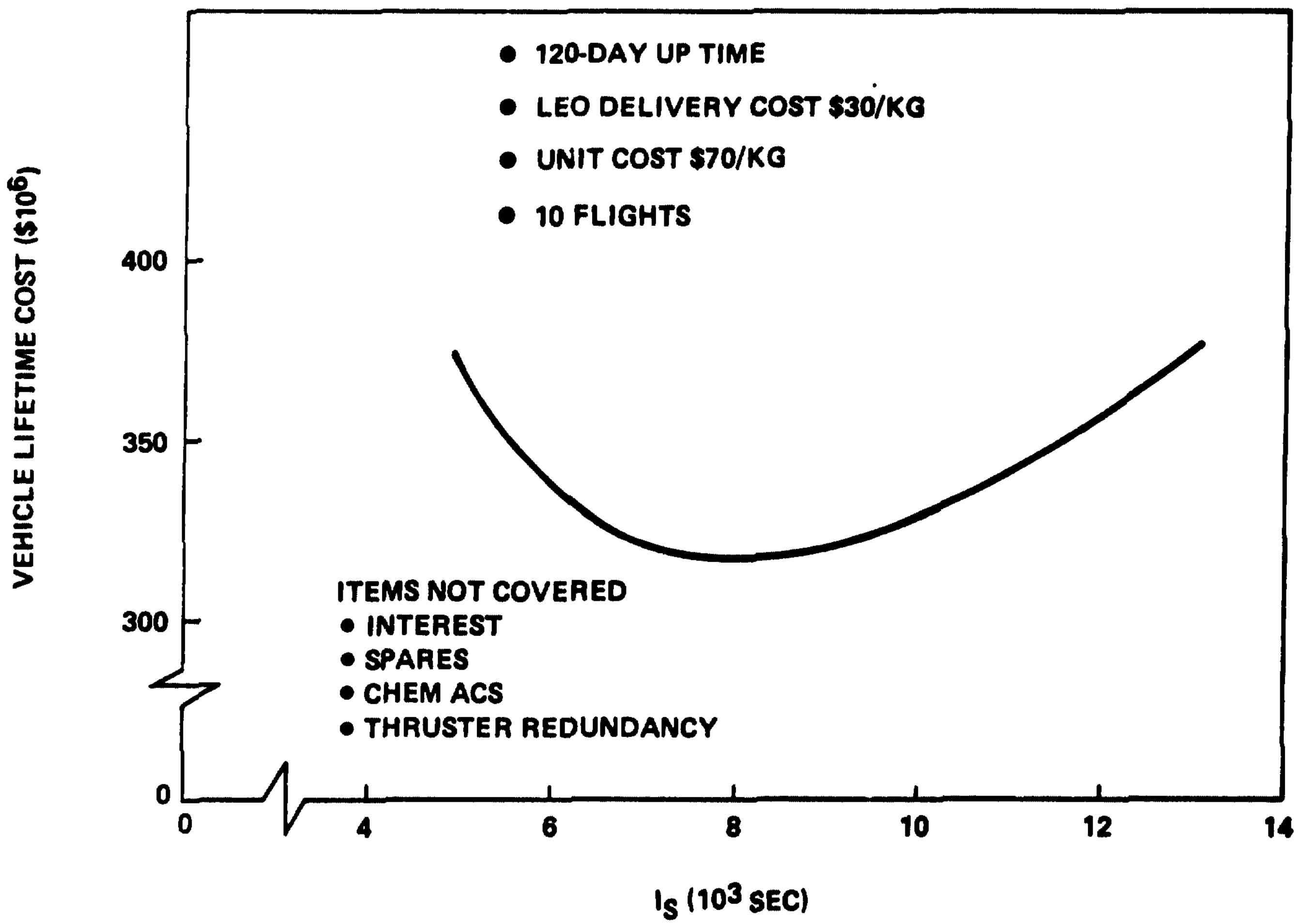
Preliminary Transfer Characteristics



PRELIMINARY IEOTV COST TRENDS

Although a complete cost analysis has not been done as yet in terms of selecting the optimum trip time, a trip time allowing two flights per year is used to illustrate the cost trends. This flight plan includes 120 days up trip time, 45 days down and 15 days for refurb, refueling and payload handling. The trend in vehicle life cycle cost as a function of specific impulse is shown. Included in life cycle cost are the basic unit costs for a vehicle as well as propellant delivery cost to perform 10 flights. All cost items have not been included as indicated, however, when they are included it is estimated that the bucket of curve will not be moved laterally but merely raised to a higher cost. With the data included thus far, the 7,000 to 8,000 seconds specific impulse appears to be optimum. When compared with the 13,000 second specific impulse, a savings of approximately $60 million per vehicle would occur. With 13 vehicles required in the basic fleet, a total savings of approximately $800 million would occur in the initial investment.

Preliminary IOETV Cost Trends



IEOTV CONFIGURATION CONCEPTS

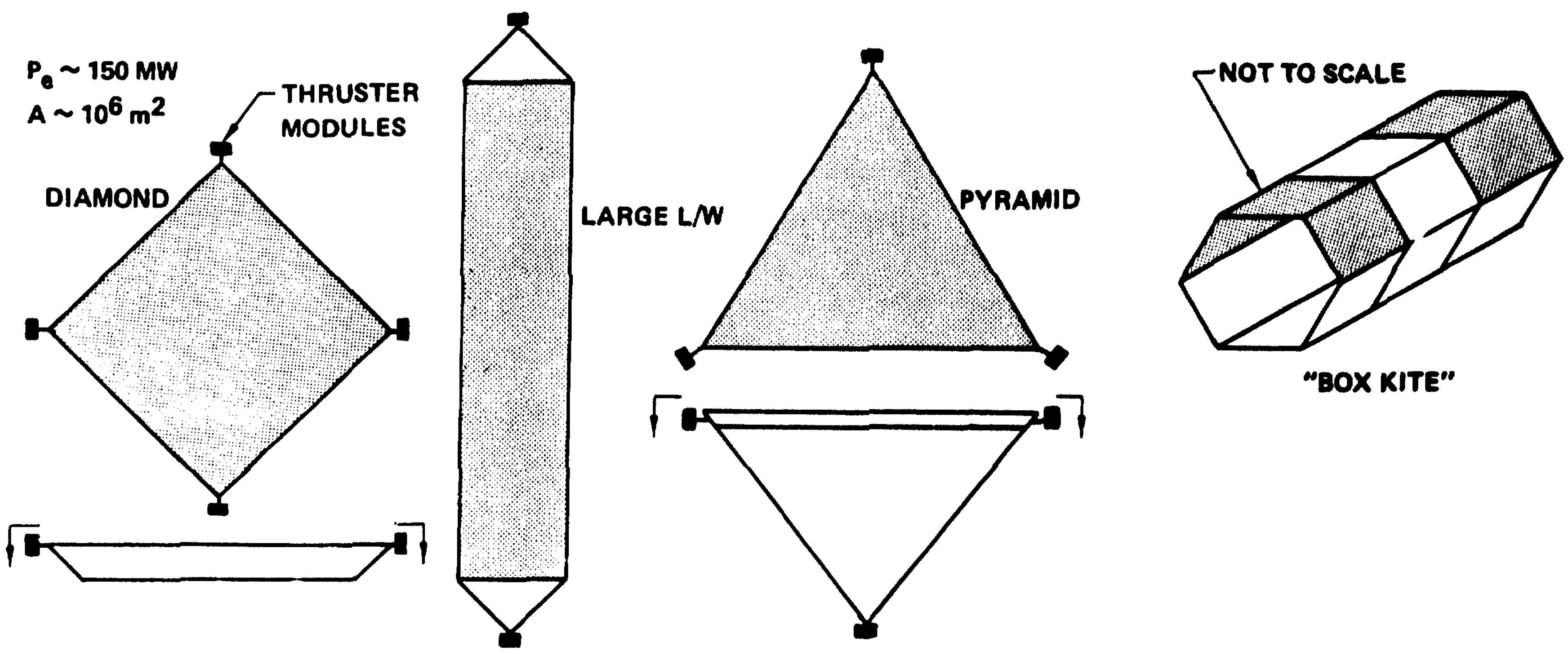
Once sizing parameters such as array size are known configurations can be developed. Several configurations alternatives have been proposed in the past with the motivation usually associated with one or more of the considerations indicated. The consideration receiving the greatest emphasis is that of gravity gradient torque (GGT), although all the considerations are significant. The diamond shaped configuration has relatively low GGT but has some thrust vector restrictions to prevent plume impingement. Large length/wide ratio configurations have a little higher gravity gradient torque than the diamond, but will have no thrust vector restrictions. The pyramid configuration was designed to have all moments of the inertia equal and, consequently, no gravity gradient torque. It has, however, thrust vector restrictions similar to that of the diamond. The fourth configuration, "box kite", developed by the Marshall Space Flight Center/Rockwell, reflects the shape of the construction base used to construct the MSFC satellite. The resulting characteristics of this design is that it would have minimum gravity gradient torque. Assessing these configuration options, several can be eliminated using the indicated criteria. The box kite concept does not have good similarity with the JSC/Boeing baseline satellite, would be more difficult to construct, and has plume impingement concerns relative to the vehicle structure. The pyramid concept also is difficult from the construction standpoint and also has thrust vector restrictions. Early assessment of the diamond and large length/wide ratio configurations indicate either concept would be acceptable. Control analysis of the diamond configurations has indicated less than 1% of the delta V capability is required to overcome gravity gradient torque. Consequently, this design appears to be quite acceptable and will be used in further configuration analysis.

IEOTV Configuration Concepts

KEY CONSIDERATIONS

- CONSTRUCTABILITY
- SIMILARITY TO SATELLITE DESIGN
- FLIGHT CONTROL GRAVITY GRADIENT TORQUE
- THRUST VECTOR RESTRICTION
- POWER DISTRIBUTION

CONCEPTS

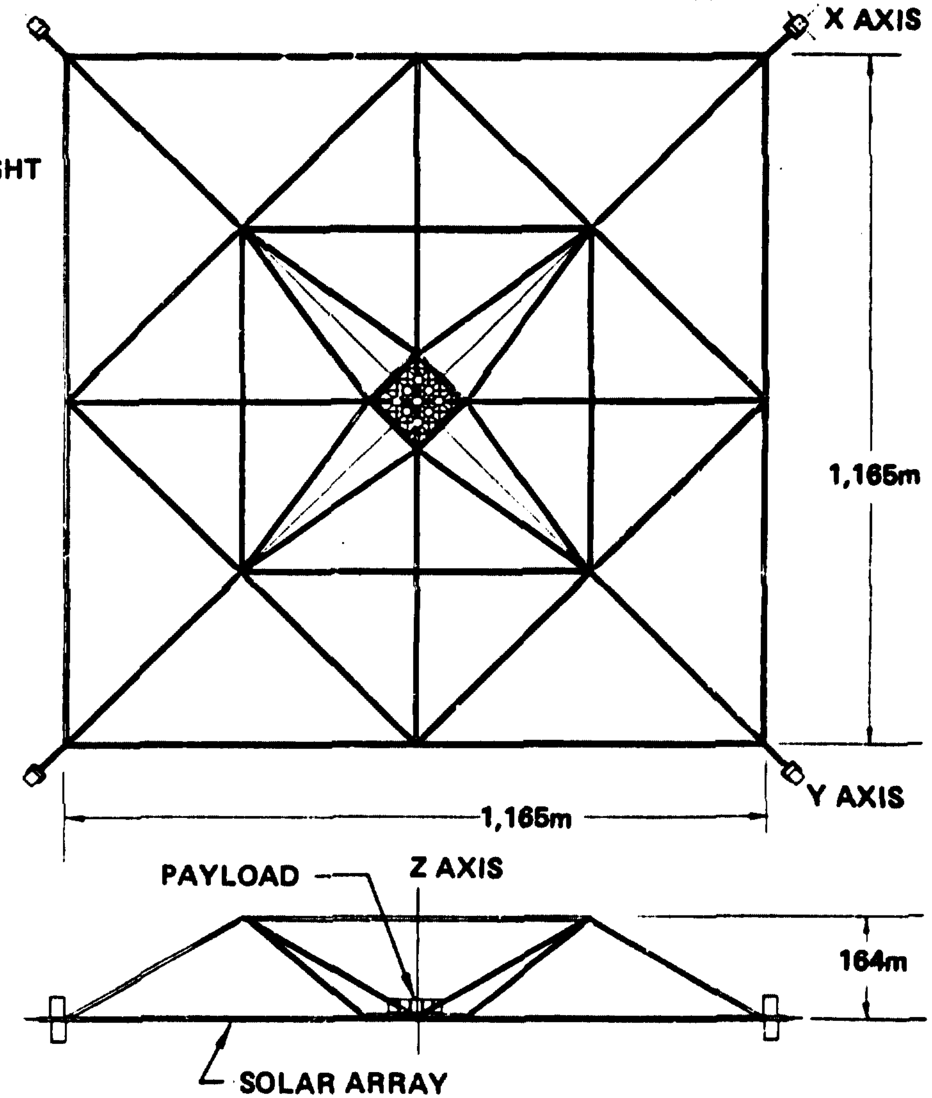


INDEPENDENT ELECTRIC OTV CONFIGURATION

A configuration for delivery of 4,000 metric tons and return of 400 metric tons is indicated. Electric power required is 200 megawatts requiring a total solar array area of 1.26 million sq meters and a thrust level of over 4,000 N. The dry mass of this vehicle is 1,530 metric tons requiring a total of 605 metric tons of argon propellant for the electric thrusters and 50 metric tons of LO_2/LH_2 propellant for supplemental attitude control.

Independent Electric OTV Configuration
Preliminary

- INITIAL POWER PER FLIGHT = 200 MW
- TOTAL ARRAY AREA = 1.26×10^6 m^2
- ELECTRIC THRUST = 4,080 N
- THRUSTERS
  - 120 cm DIAMETER
  - 1,512 UNITS
  - 7,000 SECONDS
- DRY MASS = 1,530 MT
- ARGON PROPELLANT = 605 MT
- LO_2/LH_2 PROPELLANT =



- PAYLOAD
  - UP 4,000 MT
  - DOWN 400 MT
- TRIP TIME
  - UP 120 DAYS
  - DOWN 45 DAYS

MISSION EVENTS

Some of the more significant mission events associated with a typical flight of an electric OTV are indicated. Should a total mission time of 180 days be considered along with 120 days up and 45 days down, only 15 days remain for the other functions. Future analysis will indicate the feasibility of accomplishing these functions in the designated time with particular concern associated with annealing of the solar arrays and refurb of the thrusters.

Missions Events

- TRANSFER TO GEO — COST OPTIMIZE
- UNLOAD — SEVERAL DAYS – (10) 400 MT UNITS
- ANNEAL ARRAY
  - WOULD MINIMIZE POWER GENERATION SYSTEM FOR ANNEALING MACHINES
  - WOULD RESULT IN SHORTER RETURN TRIP
- LOAD — CONTAINERS, ETC.
- TRANSFER TO LEO — DICTATED BY POWER AVAILABLE
- UNLOAD — CONTAINERS, ETC.
- REFRUBISH — THRUSTERS, ANNEAL ARRAYS
- REFUEL — ARGON, LO_2, LH_2
- LOAD — (10) 400 MT UNITS

IEOTV REUSABILITY

Although a complete reusability analysis has not been done as yet, several key issues and characteristics can be identified. In the case of hardware maintenance, the most notable requirements are those associated with the refurbishment of the solar array and electric thrusters. Using an annealing machine similar to that proposed for the satellite, a total of 250 annealing machine hours would be required to refurb the solar array of the EOTV. Chief uncertainties in the annealing operations for this type of vehicle would that of the number of annealings which are possible and the level of recovery with such deep levels of degradations as compared with the levels present with the operational satellite. As indicated earlier, the key parameter associated with electric thrusters is that of the beam current and its impact on life of the system. With 80 amps passing through the thruster it is estimated 8,000 hours of life are possible with the cathode and the grids being those components greatest concerr. Refueling of the OTV will be necessary with each mission and involve approximately 700,000 kilograms of propellant. Maintenance location is an issue in terms of whether or not the electric orbit transfer vehicle should be brought back and docked to the LEO base or remain at a station keeping location in LEO and have maintenance vehicles fly out from the LEO base.

IEOTV Reusability

SPS-2178

- HARDWARE MAINTENANCE
  - SOLAR ARRAY
    - 250 ANNEALING MACHINE HOURS (1 MILLION SQM)
    - 10 MW PER MACHINE (15m x 660m)
    - UNCERTAINTIES—NUMBER OF ANNEALINGS
      —LEVEL OF RECOVERY
  - THRUSTERS
    - FUNCTION OF BEAM CURRENT
    - 8,000 HOURS WITH 80 AMPS
    - CATHODE AND GRIDS CHIEF CONCERN
    - REPLACEMENT
      - COST——50% OF UNIT
      - MASS AND TIME——TBD
    - APPROACH
      - IN PLACE VERSUS REMOVE MODULE
- REFUELING
  - REPLACE TANK VERSUS PROPELLANT TRANSFER
- MAINTENANCE LOCATION
  - AT LEO BASE VS AT STATION KEEPING LOCATION

COST ANALYSIS

As indicated earlier, a key factor in the cost effectiveness of the GEO construction/EOTV concept will be that associated with the degree of reusability and design life of the system. This can be expressed both in terms of the number of spares required and the number of vehicles forming the fleet to transfer the components. A factor that will have a large impact on effectiveness will be the write off time associated with the vehicle and the LEO base. Production rate on the power processing units and thrusters will be less than that for the self power concept thereby having an impact on the unit cost of these systems. Two methods used to express cost will be the initial investment, which will include the fleet as well as spares required, and also the dollars per delivered kilogram of satellite which will reflect the annual operations cost as well as amortization of the initial investment.

Cost Analysis

- KEY FACTORS
  - DESIGN LIFE
    - SPARES
    - NUMBER OF VEHICLES
  - WRITEOFF TIME
  - PRODUCTION RATE ON PPU AND THRUSTERS
  - OPERATIONS COST
- AREAS
  - INITIAL INVESTMENT
  - DOLLARS/kg

Cost Preview

Although the cost analysis has not been completed at this time, the areas which will be effected and which result in a change in cost for this concept can be identified. A number of increases relative to the LEO construction, self-power concept will be present and include the basic unit cost of the electric OTV and its delivery to low earth orbit. The LEO base itself will be larger than that associated with the GEO construction/chemical OTV concept due to construction operations of the IEOTV and its maintenance. The GEO base will reflect a larger penalty due to the radiation protection required for a larger crew (500 vs 65 for the LEO construction concept). A decrease will occur, however, in the form of HLLV operations, since in the transfer of a complete satellite, a smaller amount of orbit transfer propellant will be required by the electric orbit transfer vehicle.

Cost Preview

- INCREASES RELATIVE TO LEO CONSTRUCTION AND SELF-POWER

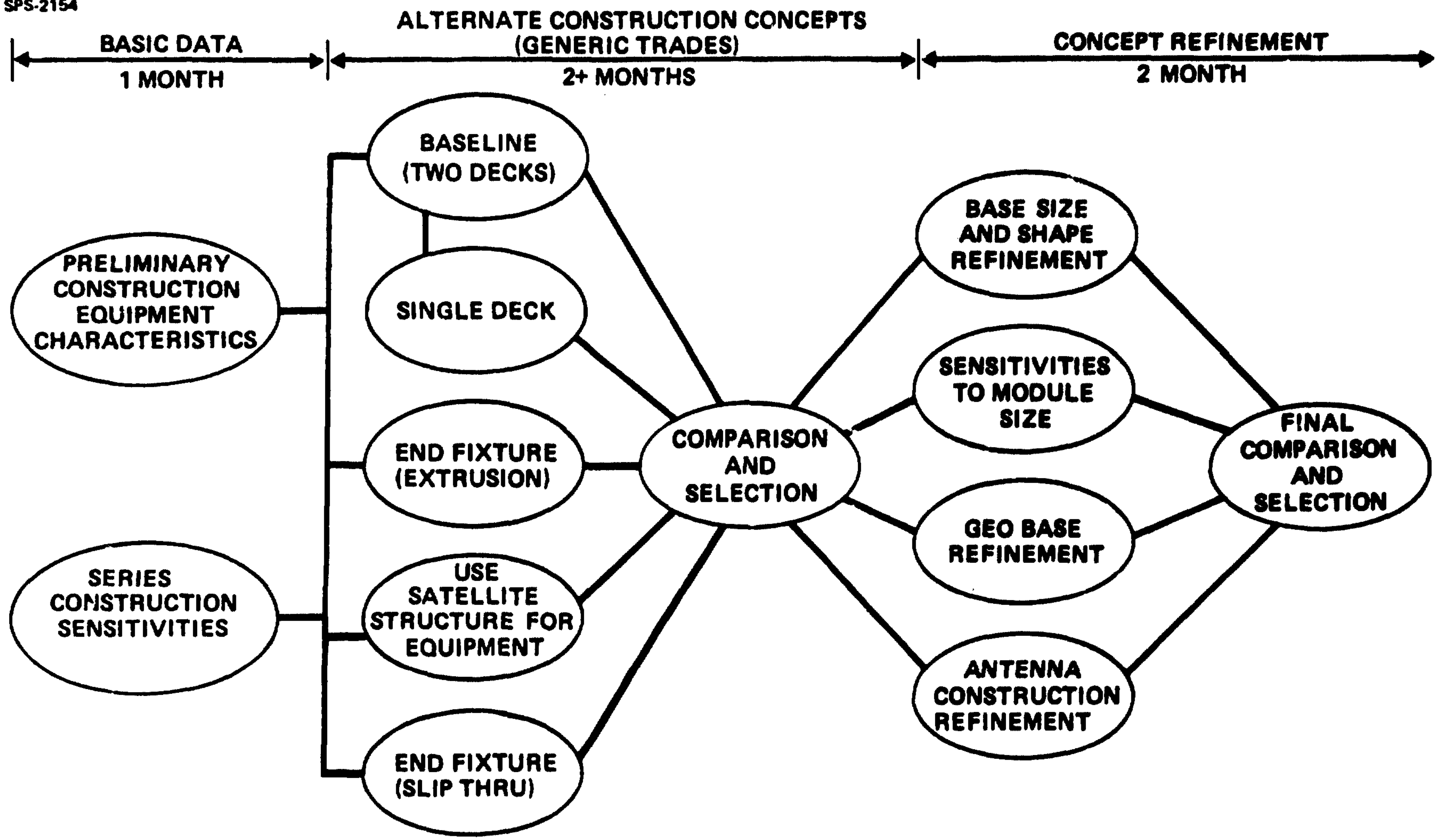
ITEM	REASON
• IEOTV UNIT COST	• POWER GENERATION AND DISTRIBUTION SYSTEM • ANNEALING SYSTEM
• HLLV OPERATIONS COST (Δ MASS TO LEO) (COST/ FLIGHT SAME AS LEO CONSTRUCTION)	• IEOTV POWER GENERATION AND DISTRIBUTION SYSTEM
• LEO BASE (RELATIVE TO GEO CONSTRUCTION)	• SIZED TO CONSTRUCT AND MAINTAIN IEOTV
• GEO BASE	• RADIATION PROTECTION
• CREW ROTATION AND RESUPPLY TRANSPORTATION	• Δ 400 CREW AT GEO • Δ CREW FOR IEOTV CONSTRUCTION AND MAINTENANCE

- DECREASES

ITEM	REASON
• HLLV OPERATIONS COST	• Δ LEO-GEO-LEO PROPELLANT

Phase 1 Construction Concept Overview

SPS-2154



SERIES CONSTRUCTION TIMELINE

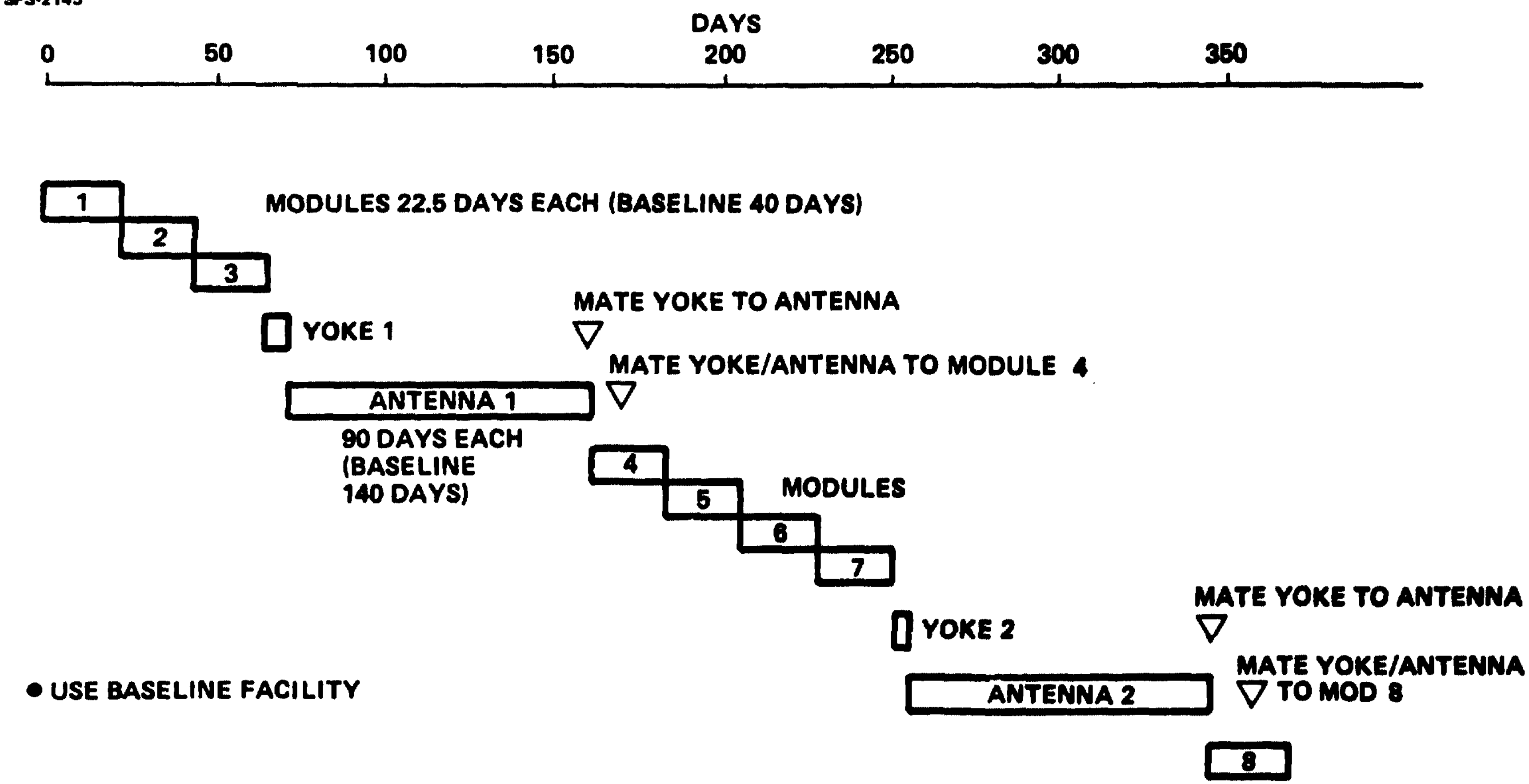
A preliminary analysis was conducted to ascertain the merits and demerits of constructing the SPS modules, yokes, and antennas in series rather than in the baseline parallel construction approach.

Baseline factors that were held constant were: 1) LEO construction, 2) baseline module, yoke, and antenna configurations, 3) one year construction time, and 4) baseline equipment configuration and operation concepts.

In the series construction concept, the first three modules are constructed, then the first yoke, and then the antenna is constructed. The module and yoke construction crew would be sent home while the antenna is constructed. After the antenna is built, the antenna crew is sent home and the module crew is returned.

Alternative facilities were considered, but due to operational complexities of these alternatives, it was elected to stay with the baseline LEO facility.

Series Construction Timeline



SERIES CONSTRUCTION LEO BASE RATES AND QUANTITIES

In order to fabricate the modules and antennas in about half the time that was available when using parallel construction, there are two options: Option 1 - use faster construction equipment rates, or Option 2 - use more equipment while keeping the rates the same as the baseline.

The table shows the comparison of the equipment rates, quantity of equipment items, and the crew sizes for these two options and the baseline concept. At this point in time it is uncertain whether or not the baseline equipment rates are reasonable. Grumman will be analyzing the baseline equipment concepts and will make judgements of how realistic the allocated rates are.

As the reasonableness of the rates are still undefined, the Option 2 concept assumes that it is necessary to double all of the critical construction equipment quantities in order to keep the rates approximately the same as the baseline. This would probably not be necessary for all of the machine types so the Option 2 data represents a conservative upper bound.

Series Construction LEO Base Rates and Quantities

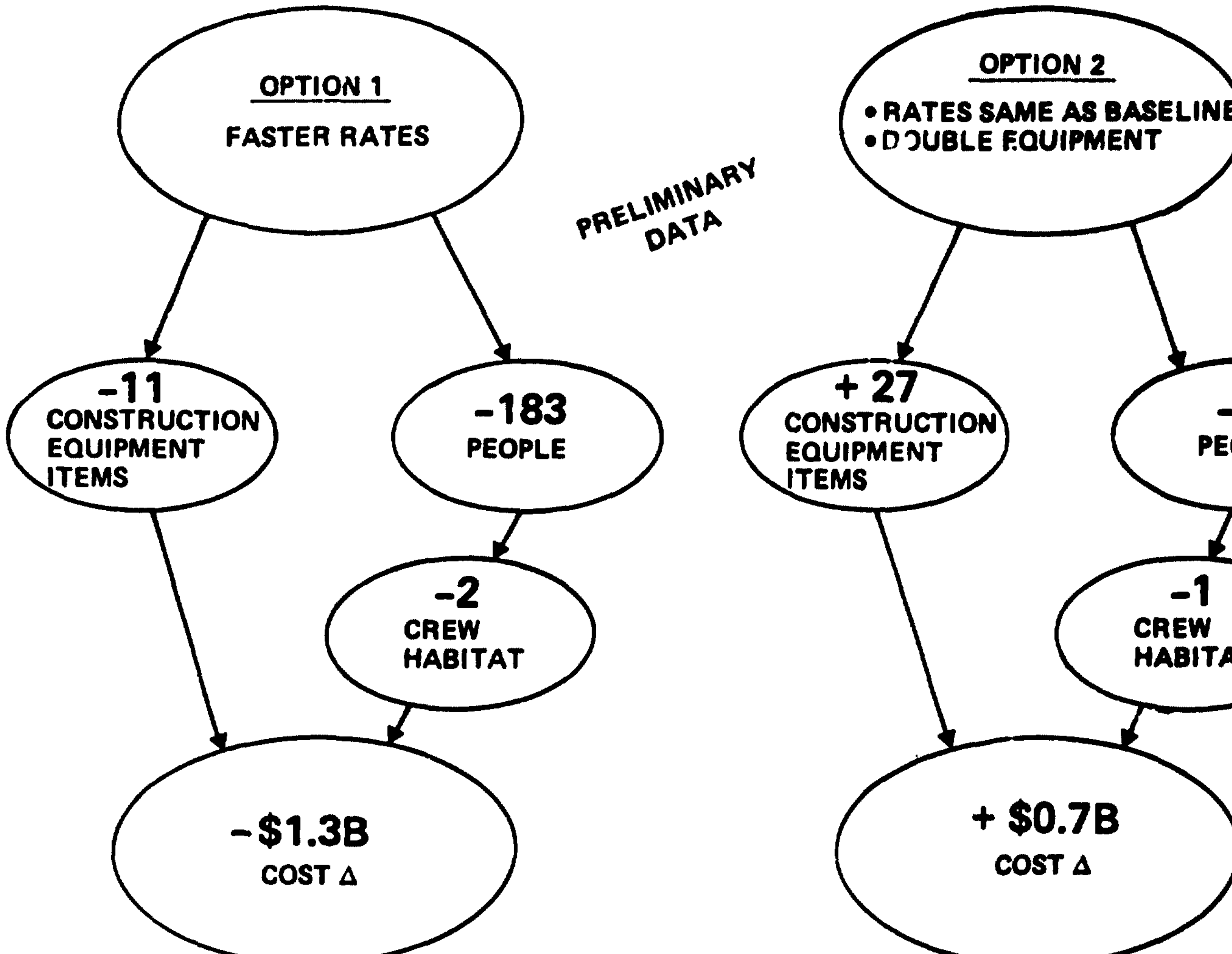
SPS-2146

	BASELINE	SERIES	
		OPTION 1 FASTER RATES	OPTION 2 MORE EQUIPMENT
EQUIPMENT RATES			
BEAM MACHINE	5.06 m/min	10 m/min	5 m/min
SOLAR ARRAY DEPLOYERS	12.6 m/min	23.7 m/min	10.2 m/min
SUBARRAY DEPLOYERS	20 min/SUBARRAY	12.9 min/SUBARRAY	25.7 min/SUBARRAY
POWER BUS DEPLOYERS	0.7 m/min	1.2 m/min	0.6 m/min
EQUIPMENT QUANTITY			
BEAM MACHINES	2	2	4
SOLAR ARRAY DEPLOYERS	4	4	8
SUBARRAY DEPLOYERS	1	1	2
CRANE/MANIPULATORS	31	23	46
POWER BUS DEPLOYERS	3	2	4
CREW SIZE			
MANAGEMENT	10	10	10
CONSTRUCTION	362	239	314
BASE OPERATIONS	39	39	39
BASE SUPPORT	77	57	77
	488	345	440

SERIES CONSTRUCTION OPTIONS

This chart shows the preliminary measures of the two series construction options as compared to the baseline parallel construction concept.

Series Construction Options

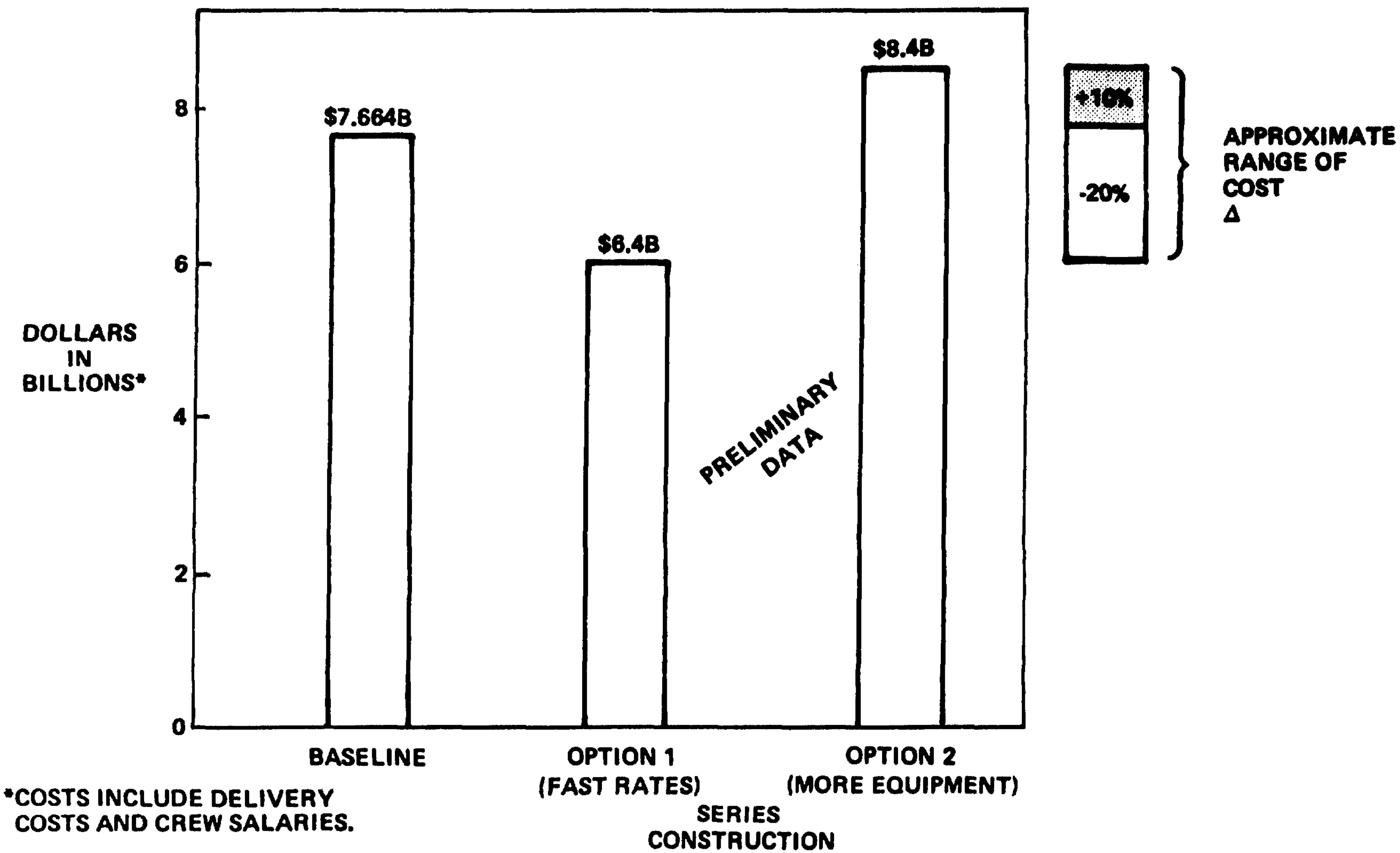


SERIES CONSTRUCTION COST DELTAS

The first unit costs associated with the two series construction options and the baseline concept are shown in this chart. These costs include crew salaries and delivery costs that were not included in cost statements shown in Part III baseline cost statements.

The preliminary data shows that if faster equipment rates can be achieved (Option 1) as much as 20% savings can be realized. This is primarily due to eliminating two crew habitats.

Series Construction Cost Deltas



*COSTS INCLUDE DELIVERY COSTS AND CREW SALARIES.

SERIES CONSTRUCTION PRELIMINARY CONCLUSIONS

Series construction could result in significant savings when compared to the baseline parallel construction. The exact amount will be determined after the generic construction facility concept is selected, the construction equipment is characterized in more detail, and the crew module costs are updated.

Series construction does have the disadvantage that there will be idle equipment (antenna construction equipment is idle during module construction and vice versa), there would be operational inefficiences resulting from the discontinuous production of the major end items, and there would be inventory control and warehousing complications.

Series Construction Preliminary Conclusions

- SERIES CONSTRUCTION MAY RESULT IN +10% TO -20% COST Δ
  - EXACT Δ WILL DEPEND UPON–
    - GENERIC CONSTRUCTION FACILITY CONCEPT SELECTION
    - CONSTRUCTION EQUIPMENT RATE, COST, AND MASS DEFINITION
    - CREW MODULE COST AND MASS DEFINITION
- ADVANTAGES:
  - POTENTIAL COST SAVINGS
- DISADVANTAGES:
  - IDLE EQUIPMENT
  - DISRUPTION IN PRODUCTION CONTINUITY
  - WAREHOUSING AND INVENTORY CONTROL COMPLICATIONS

SINGLE-DECK CONSTRUCTION BASE

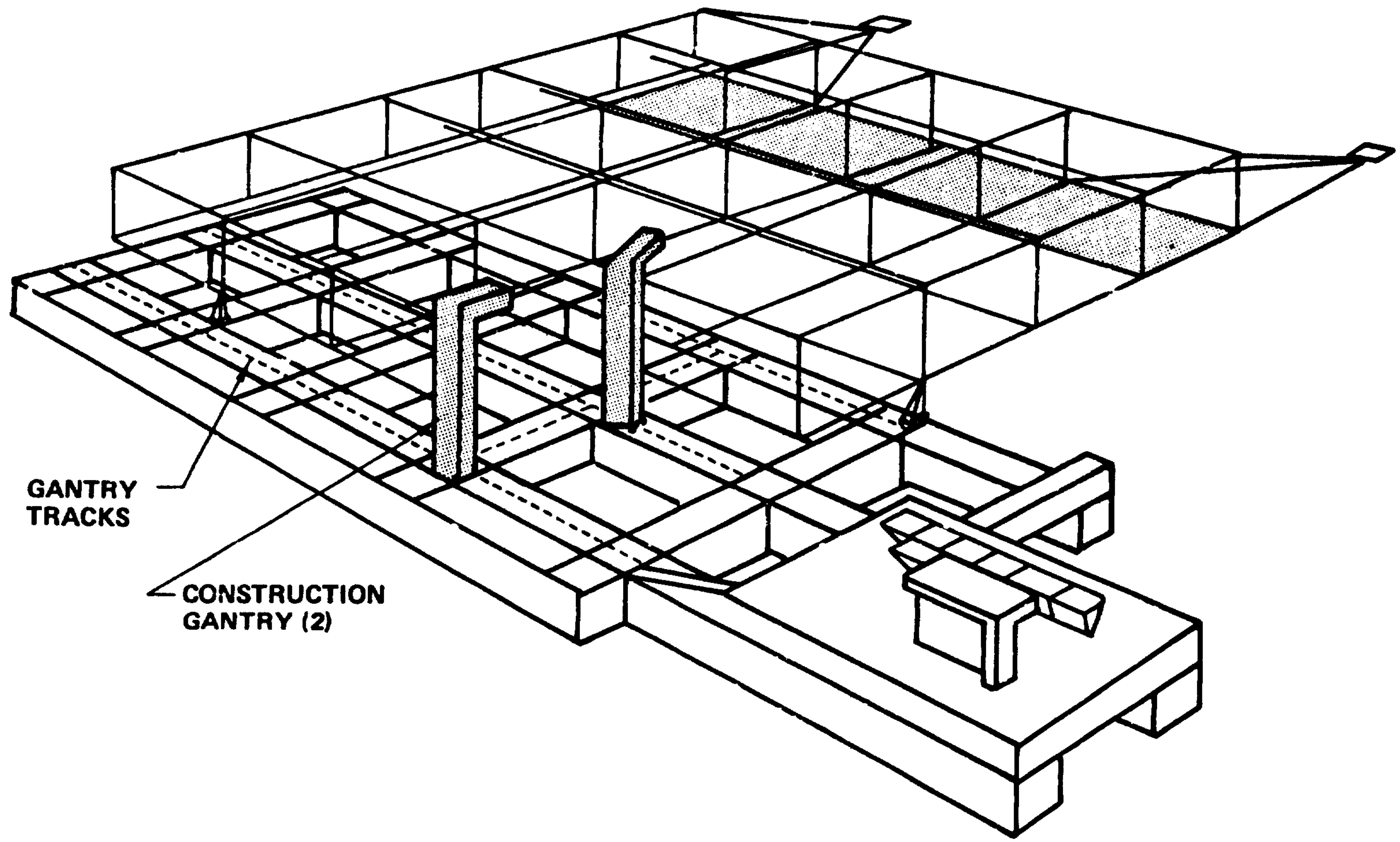
The single-deck construction base is a derivative of the baseline LEO base. In this concept, the "roof" and "back wall" of the baseline facility have been eliminated by moving the facility to module indexers to the lower level and by using two construction gantries (the gantries are described in the following chart).

The indexers would operate from the track network that is used by the construction and logistics equipment. The track pattern defined in the Part III studies provides enough alternative pathways that competition for track locations between the indexers and other equipment does not appear to be a problem.

The construction gantries would operate from a dedicated track network due to the large wheelbase required for these large machines.

The antenna facility retains the C-clamp configuration due to the multiple number of installation operations that occur on both faces of the antenna structure.

Single-Deck Construction Base

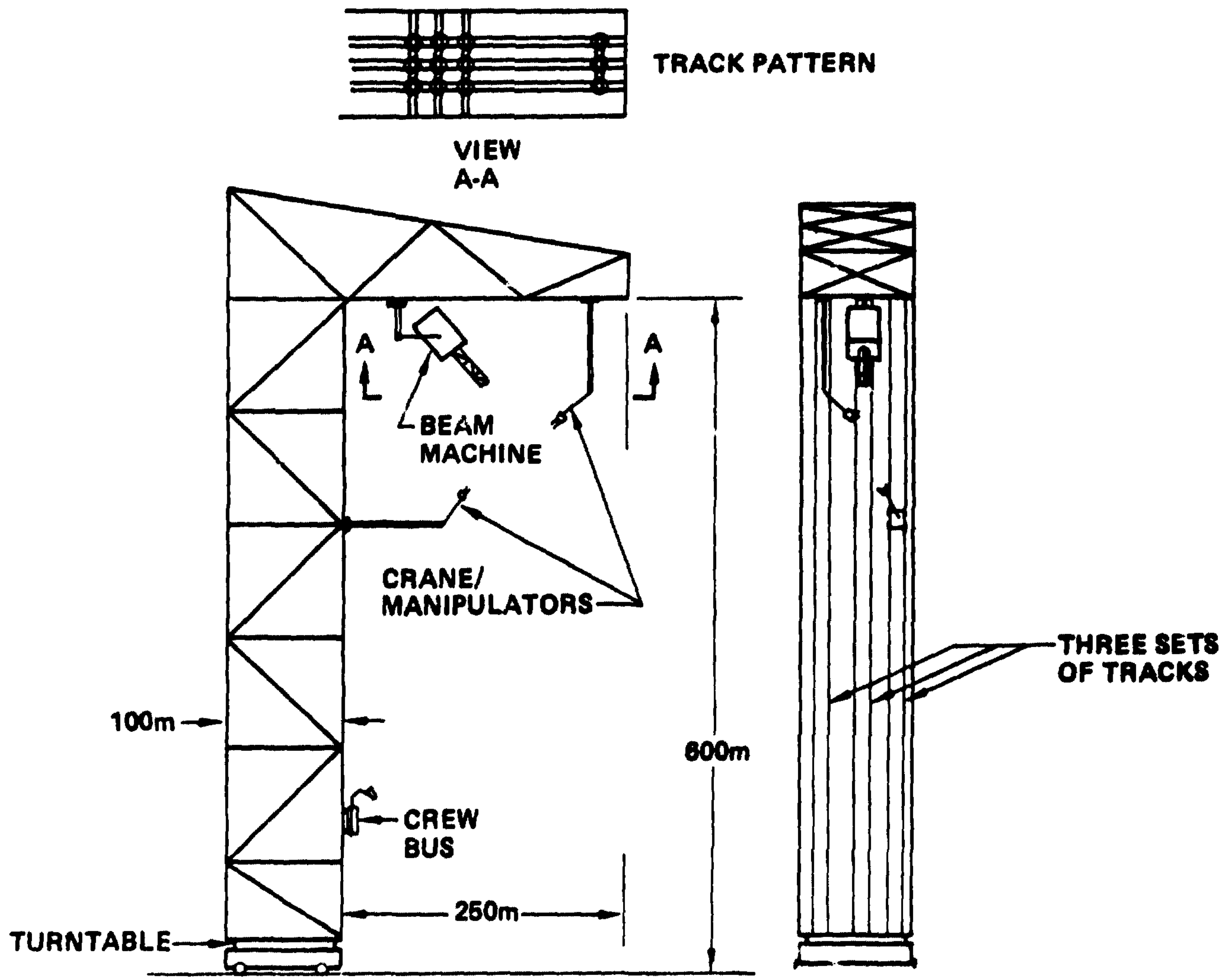


600m GANTRY CONFIGURATION CONCEPT

The construction gantries provide the working surfaces for the beam machines and crane/manipulators that are used to fabricate and assemble the upper surface of the module and yoke (only one of the gantries would have a beam machine attached). The construction equipment would be capable of moving about on the track network built into the gantry. A crew bus would be installed on each gantry to transport the crews from the platform to the construction equipment.

600m Gantry Configuration Concept

SPS-2144



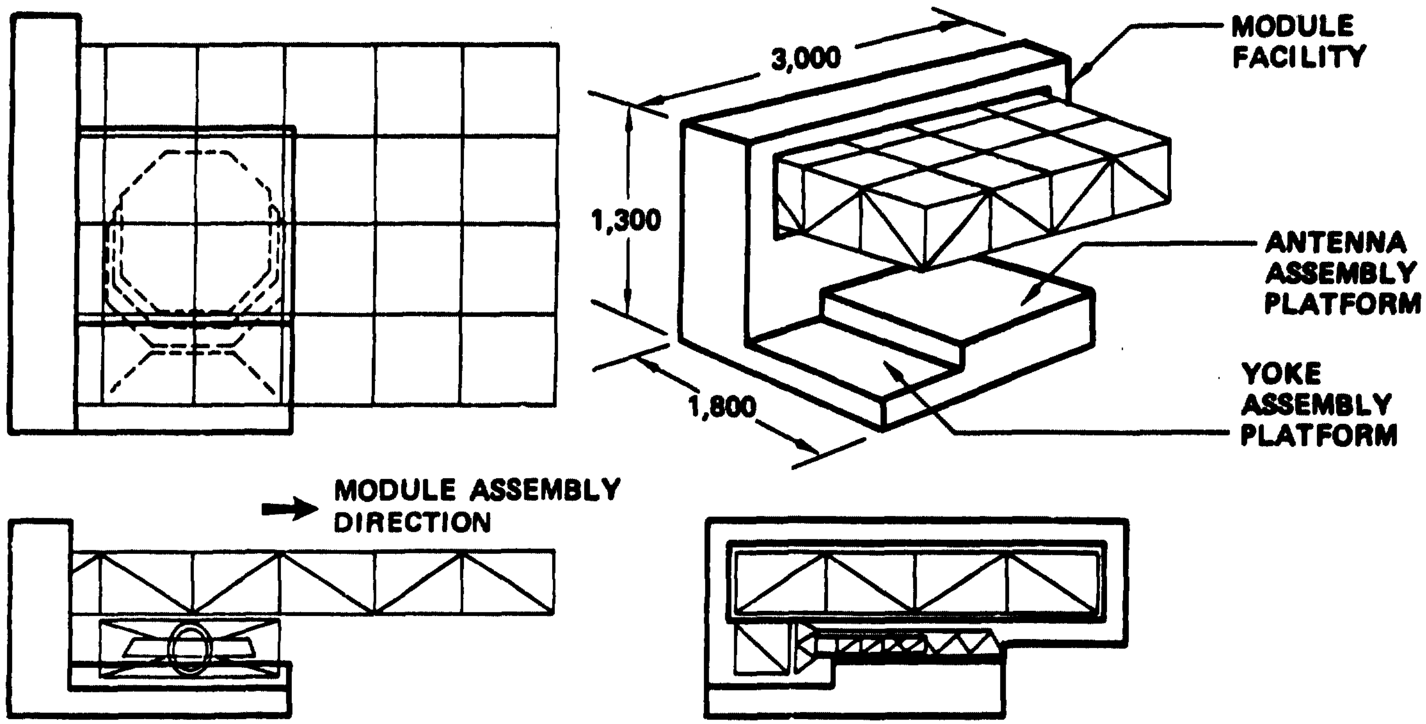
END JIG FACILITY

The so-called "End Jig" facility concept represents a generically different approach to satellite construction as compared to the baseline concept. In this concept, the module would be "extruded" from a facility by the simultaneous fabrication of the longitudinal beams. The "extrusion" action could be employed to deploy the solar array blankets. The extrusion process would be stopped at the end of each bay to allow the lateral beams and solar array containers to be installed.

In the end jig concept shown, the antenna and yoke assembly operation would be performed on a platform located below the module. These units would be assembled in a position where they could be joined to the module in the orientation in which the antenna would be located for transport.

There are several issues that will need to be resolved to implement the end jig concept. Frame indexing/support and simultaneous beam assembly are the primary problems.

End Jig Facility



- CHALLENGES
  - FRAME INDEXING AND SUPPORT
  - SIMULTANEOUS AND SYNCRONIZED BEAM MACHINE OPERATIONS
  - DIAGONAL AND LATERAL BEAM FABRICATION AND ASSEMBLY
  - SOLAR ARRAY DEPLOYMENT

2.5 GW SOLAR POWER SATELLITE (SPS)
IR&D RESULTS

A Boeing independent research effort is underway to gain a preliminary understanding of the value of a 2500 MW ground output SPS as either:

1) A large developmental unit

2) A production unit.

Motivations for this effort include possible lower development funding and improved utility "capacity credit" for a smaller SPS.

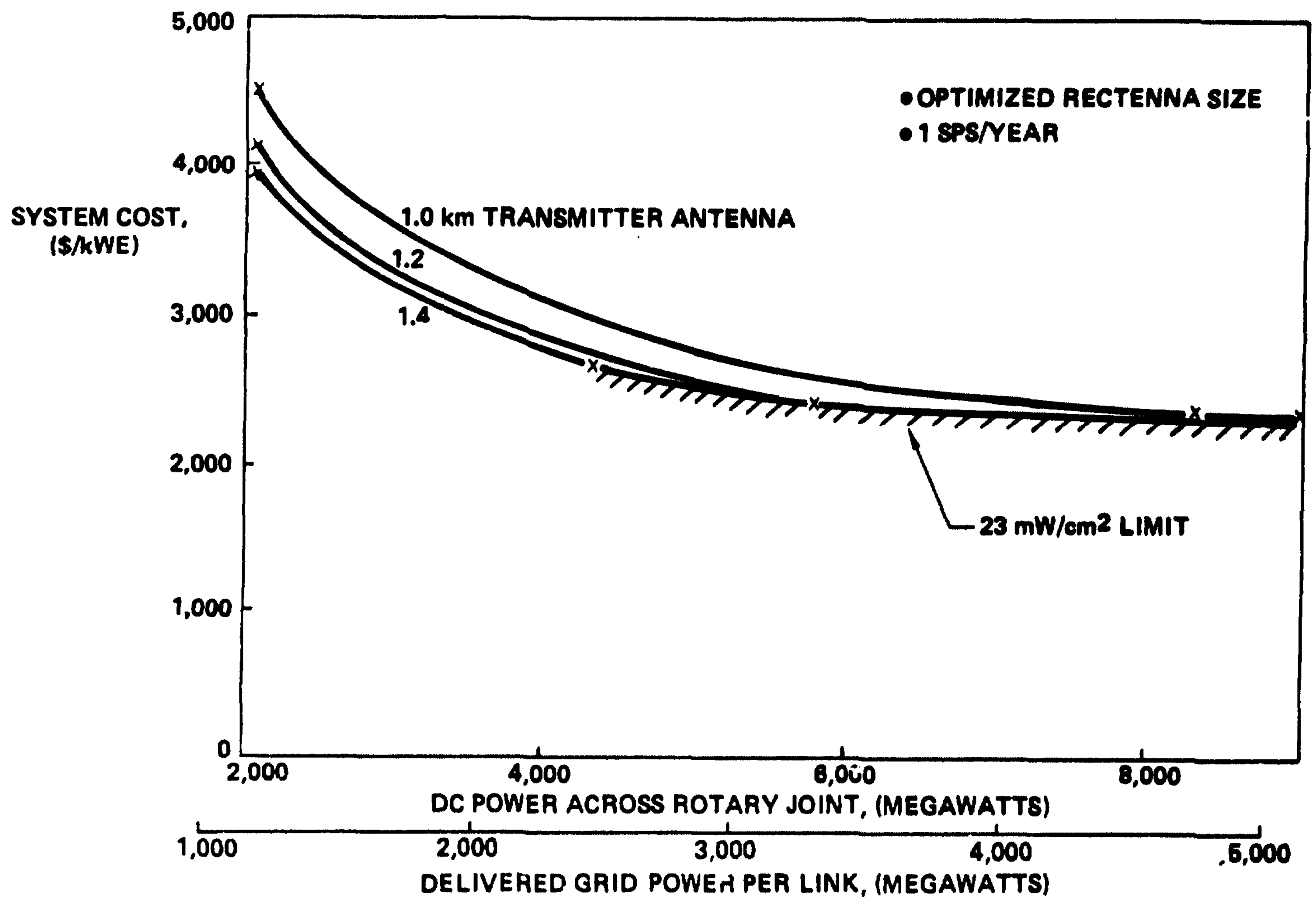
BOEING
SPS

2.5-GW Solar Power Satellite (SPS) IR&D Results

SIZE SENSITIVITY ANALYSIS: POWER LEVEL AND TRANSMITTER DIAMETER

This chart was developed during Part III of contract NAS9-15196 and is the result of computer processing of a SPS systems model. It was shown that minimum overall SPS cost might be obtained when the space transmitter diameter was about 1.4 km in diameter, since this caused the ground receiver to be smaller (than, for example, with a 1.0 km transmitter). However, large transmitters result in exceeding the current 23 m W/cm^2 "limit" on ionospheric power density, unless the delivered grid power is 2500 MW or less. Hence it may be possible to have smaller SPS without a significant recurring cost penalty.

Size Sensitivity Analysis Power Level and Transmitter Diameter



GROUND RULES

These ground rules apply to the Boeing independent study of the 2.5 GW SPS.

BOEING SPS

Ground Rules

78-131

- SAME TECHNOLOGY LEVEL AS CURRENT SILICON SPS
- 15-YEAR CONSTRUCTION PROGRAM, 40 UNITS (= 100 GW)
- 70 kW KLYSTRON, IF POSSIBLE
- $\geq$23 mW/cm^2 CENTRAL BEAM
- FIRST BEAM NULL LESS THAN 0.1 mW/cm^2
- BOOST BY EITHER THE CURRENT TWO-STAGE, WINGED HLLV OR BY A SHUTTLE DERIVATIVE
- LOW-ORBIT ASSEMBLY
- SELF-POWER TRANSFER TO GSO (MONOLITHIC, IF POSSIBLE)

This Work Accomplished
Using Boeing IR&D Funds

MICROWAVE CONSIDERATIONS

Compared to the 1.0 km diameter antenna of the 5.0 GW ground output system, the 1.4 km antenna has approximately:

1. One half the transmitter tube mass
2. Twice the waveguide mass

A preliminary estimate indicates that the specific mass (total orbital system mass divided by delivered grid output) is 19% higher for the 2.5 GW unit.

BOEING SPS

Microwave Considerations

78-132

- WITH THE GROUND-RULED PARAMETERS FIXED, THE PRODUCT OF THE APERTURES IS NEARLY CONSTANT.
- WITH HALF THE TRANSMITTED POWER, THE TRANSMITTER AREA IS NEARLY TWICE, AND THE RECTENNA AREA NEARLY HALF OF THE 5 GW SYSTEM
- HENCE: TRANSMITTER DIAMETER WILL BE APPROXIMATELY 1,440M
  RECTENNA EAST-WEST WIDTH APPROXIMATELY 7.0 km
- MASS IMPACT (GROWTH NOT INCLUDED)

ANTENNA ELEMENTS	5 GW (METRIC TONS)	2.5 GW (METRIC TONS)
STRUCTURE	250	505
WAVEGUIDE	2,157	4,314
KLYSTRONS	6,790	3,395
CONTROL SYSTEMS	500	250
POWER DISTRIBUTION	501	460
POWER PROCESSING	2,520	1,260
	12,718	10,179
POWER GENERATION	26,859	13,430
	39,577	23,609
kg/kW RECEIVED	7.92	9.44

$$\frac{9.44}{7.92} = 1.19$$

This Work Accomplished
Using Boeing IR&D Funds

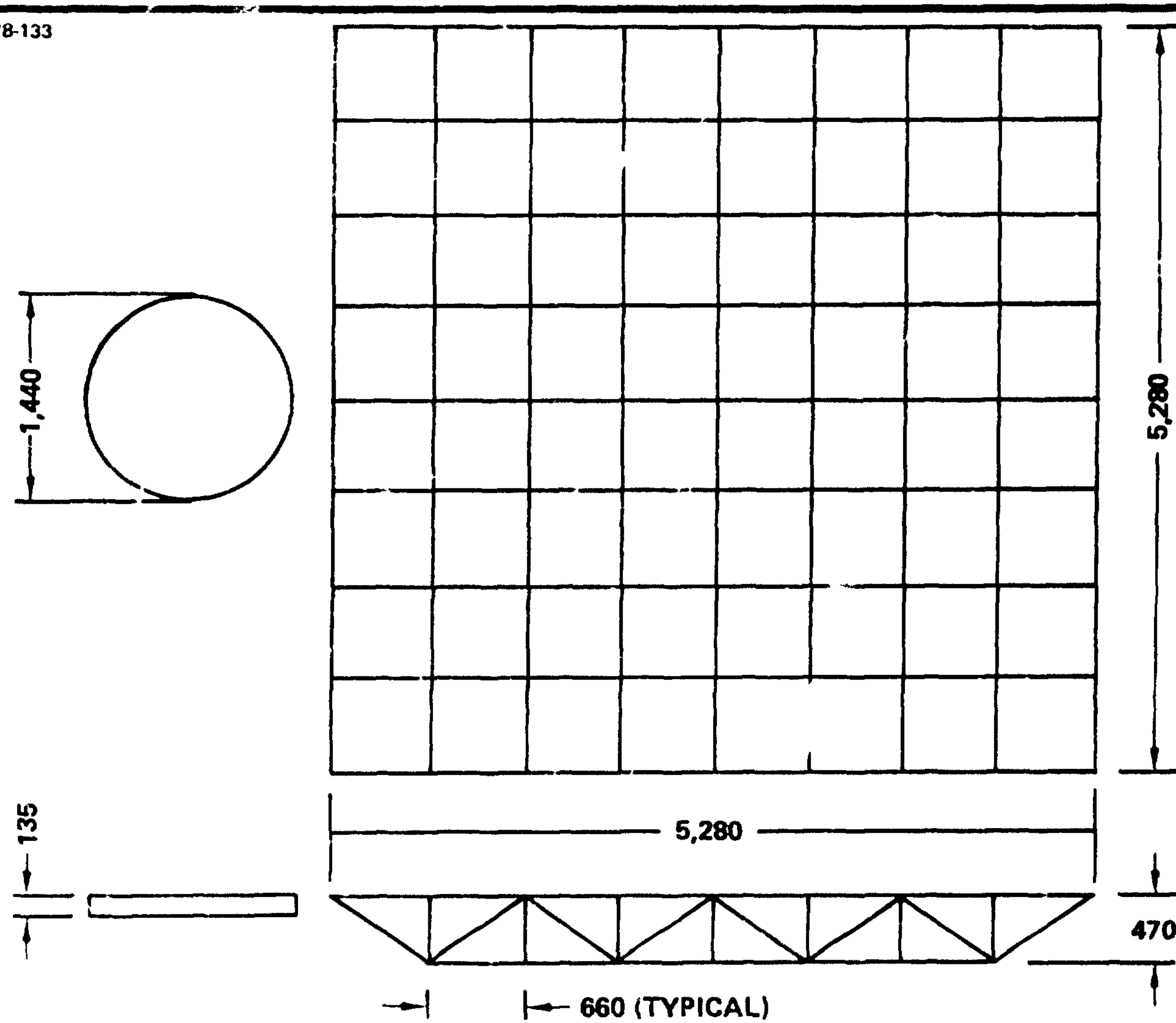
2.5 GW SPS CONFIGURATIONS

This shows a preliminary sizing of a system to deliver 2.5 GW. In accordance with a preliminary construction analysis, the bay size is the same (660 m) as the 5.0 GW "reference" design from contract NAS9-15196. The "beveled edges' can be used since the monolithic structure does not involve modules which must mate edge to edge. The antenna would be rotated to the center of the "bottom" side during self power transport; thrusters would be located at the four corners.

BOEING SPS

2.5-GW SPS Configuration

78-133



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Using Boeing IR&D Funds

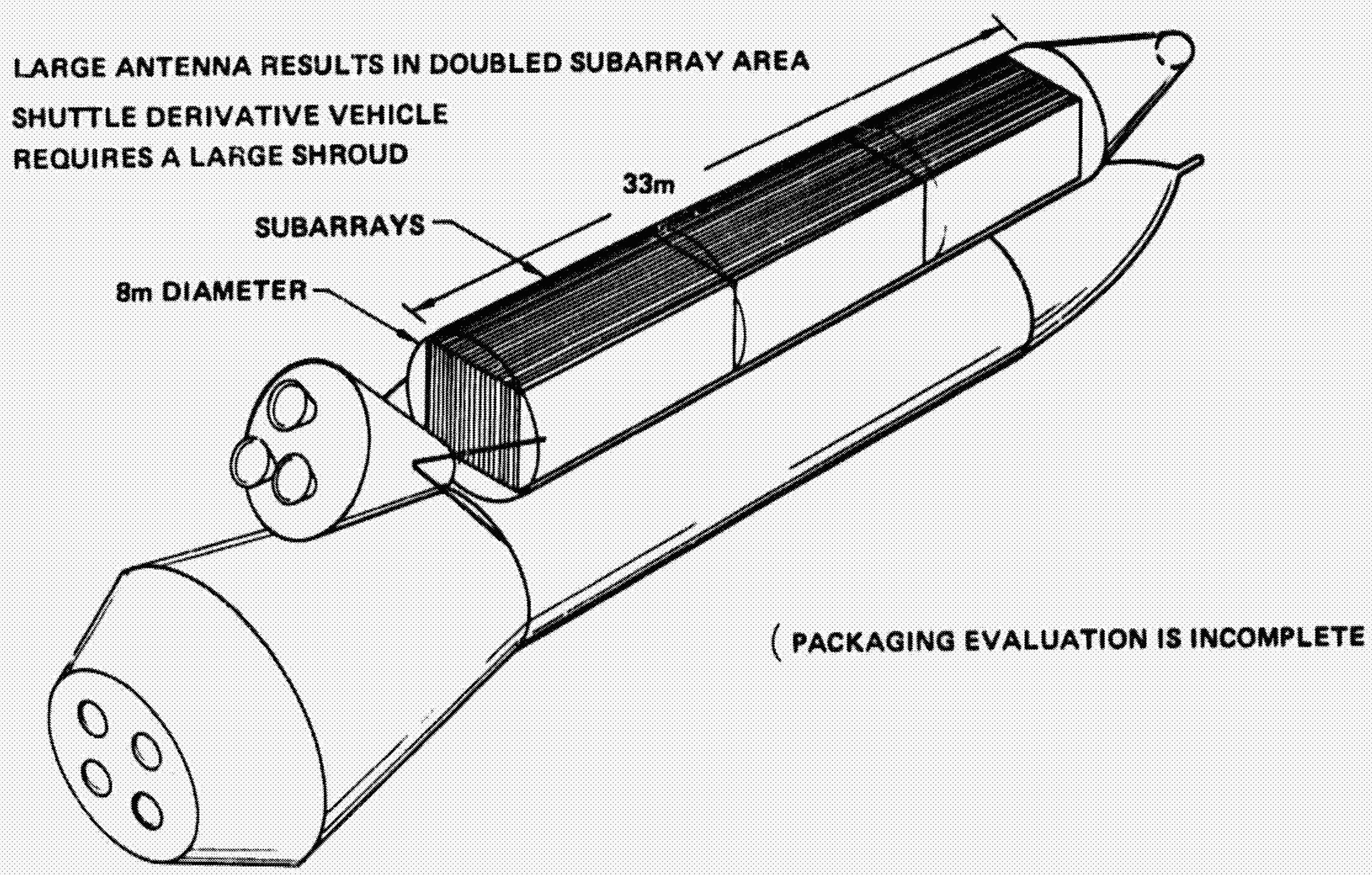
SHUTTLE DERIVATIVE VEHICLE CHARACTERISTICS

Analysis under contract NAS9-15196 indicated that transmitter subarrays should be launched from Earth as completely assembled units. The low density subarrays constituted the majority of the volume to be carried to orbit. For a 2.5 GW SPS, with twice the subarray area per delivered ground kw, the packaging task is even more challenging. If the initial unit is to be launched by a derivative of the space shuttle, a high volume shroud will be required; a possible arrangement is shown.

BOEING
SPS

Satellite Derivative Vehicle Characteristics

78-134



This Work Accomplished
Using Boeing IR&D Funds

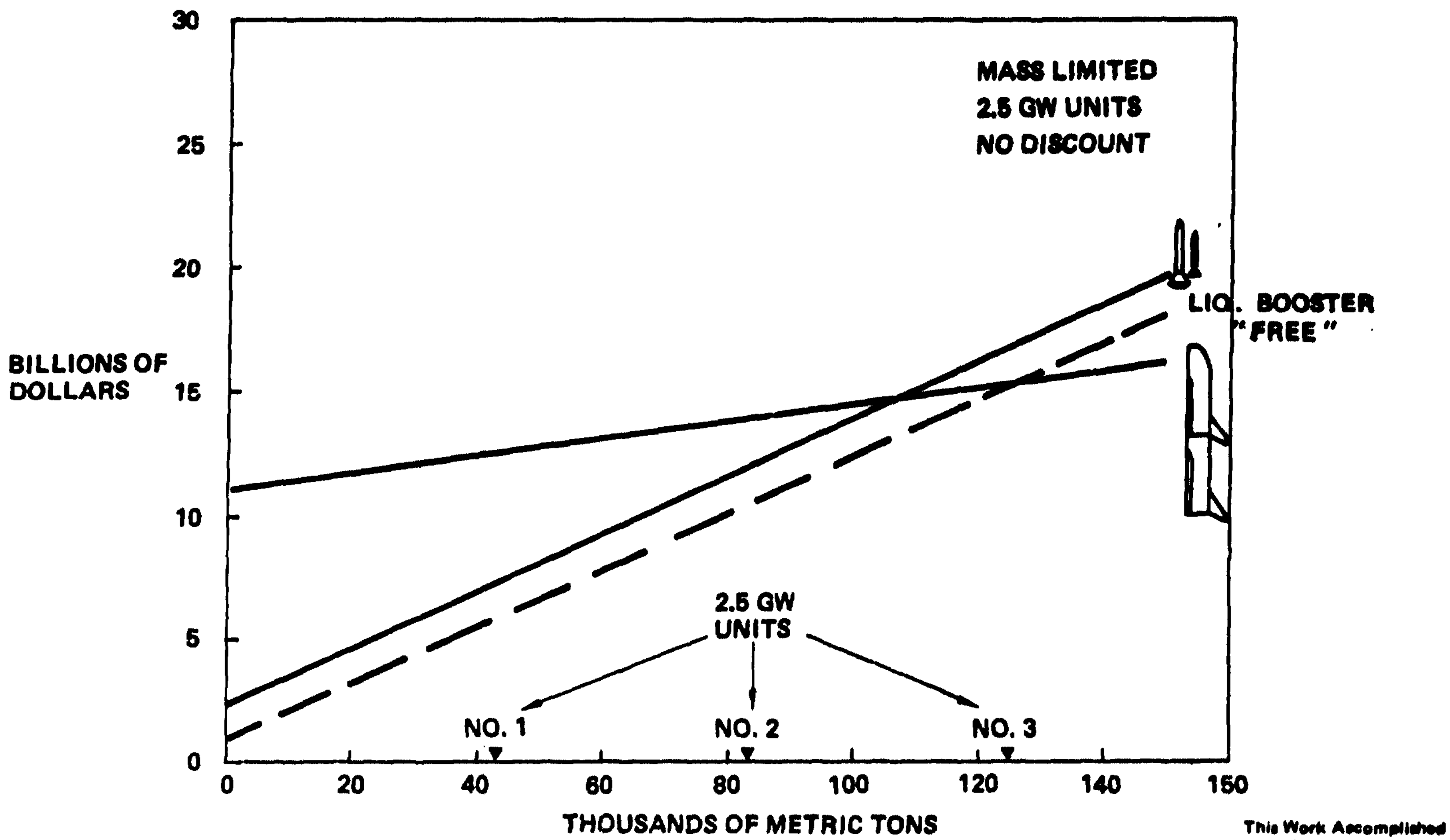
BOOST COST EFFECTS

A shuttle derivative launch vehicle (SDLV) will have a lower development cost than the large heavy lift launch vehicles (HLLV) currently proposed for SPS; however, the recurring cost (per delivered kilogram) would be much higher. If a SDLV is used to launch an initial 2.5 GW SPS, total program funding to the point of "system on the line" will be approximately \$5B less than if the HLLV were used.

BOEING SPS

Boost Cost Effects

78-135



This Work Accomplished Using Boeing IR&D Funds

SMALLER SATELLITE CONSTRUCTION ISSUES

The 2.5 GW SPS construction analysis has yielded several general conclusions.

The module an antenna frame bay sizes should be made as large as practical. The longer the bay size, the fewer joints that need to be assembled. More importantly, the longer the bay size, the fewer indexing maneuvers are required.

The solar array blanket width should be as large as allowed by the earth-to-LEO cargo vehicle payload bay size. The wider the blankets, the fewer that need to be installed.

The subarrays should also be as large as possible. It is particularly important to avoid having to subassemble subarrays at the LEO base.

The facility size is dictated by the bay sizes used in the power collection module and in the antenna. If these dimensions are similar to those used on a 10 GW SPS, then the overall facility platform area will be similar.

The module and antenna construction crew sizes will be similar to those required to make the large SPS because the construction operations are the same. By using series construction, the total crew size can be reduced by changing out the module construction crew and bringing up the antenna crew after the yoke is constructed.

BOEING SPS

Smaller Satellite Construction Issues

78-136

- MAXIMIZE BAY SIZE (FEWER JOINTS — LESS ASSEMBLY TIME)
- MAXIMIZE SOLAR ARRAY BLANKET WIDTH (FEWER BLANKETS — LESS INSTALLATION TIME)
- MAXIMIZE SUBARRAY SIZE (FEWER SUBARRAYS — LESS INSTALLATION TIME, LARGER SIZE — LESS SUBASSEMBLY — FEWER PEOPLE)
- FACILITY WILL NOT NECESSARILY BE SMALLER THAN THAT USED TO CONSTRUCT LARGER SATELLITES (FACILITY DIMENSIONS PROPORTIONAL TO BAY SIZE)
- MODULE AND ANTENNA CONSTRUCTION CREW SIZES, SAME AS THOSE FOR 10 GW (THE SAME CONSTRUCTION OPERATIONS MUST BE PERFORMED)

This Work Accomplished
Using Boeing IR&D Funds

2.5 - GW SPS - INDEPENDENT STUDY

The 2.5 GW SPS could be constructed using a single-deck LEO facility such as shown here. This facility would be used to construct the entire SPS at LEO (i.e. self power transfer would be for the entire, non-modular unit).

Two movable construction gantries are used to provide working surfaces for the equipment that is used to assemble the top surface of the power collection module. The module is supported and indexed from the module assembly platform tracks by indexers. Lateral and longitudinal indexing is required.

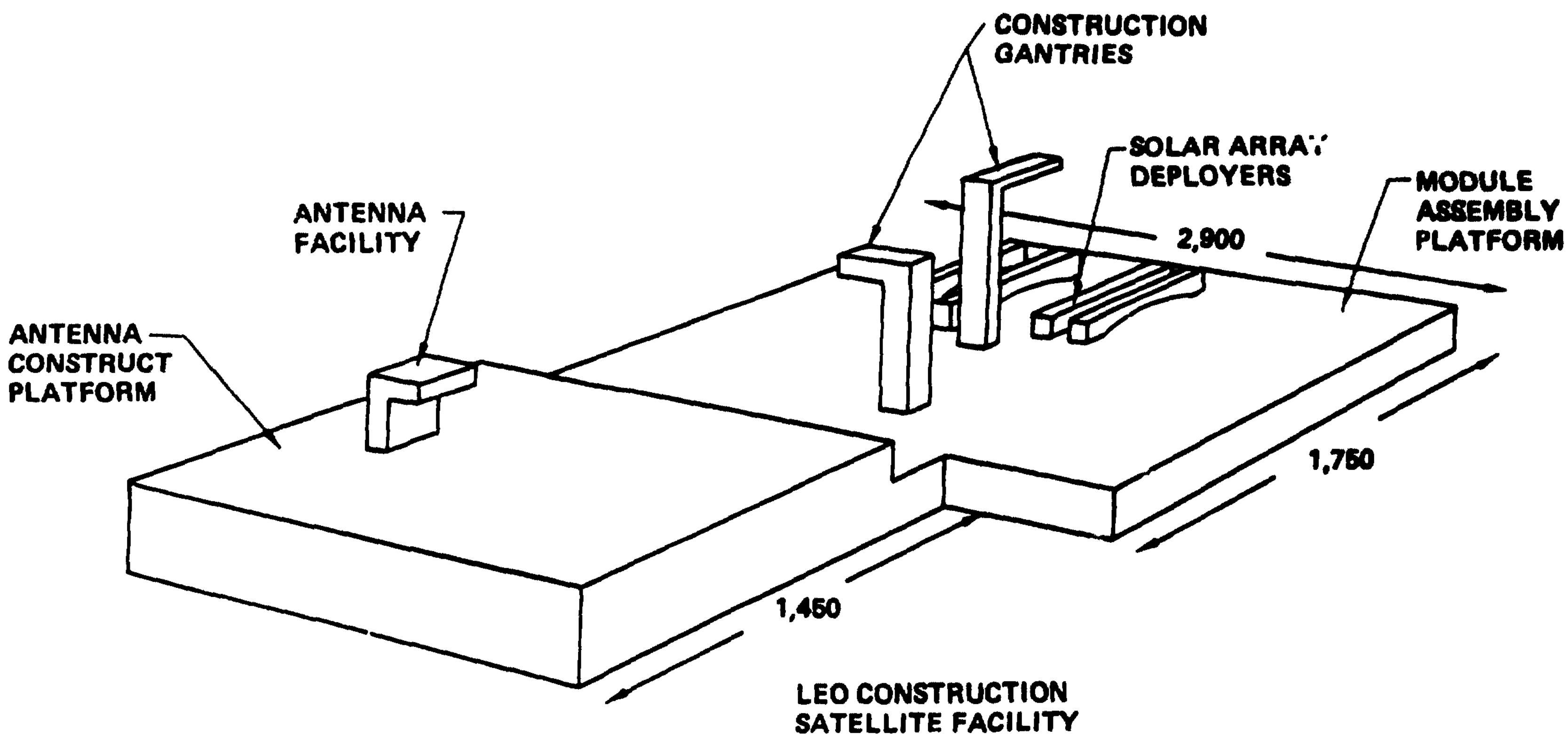
Using an approach wherein the power collection module, the yoke, and the antenna are constructed in series, 90 days are required to construct the module, 10 days to construct the yoke, and 175 days to construct the antenna. A crew size of 478 (the same as the baseline 10 GW SPS base crew size) would be at the LEO base for the first 100 days and 350 would be required for the last 175 days.

The same types and quantities of construction equipment as were defined for the 10 GW SPS construction would be required. The quantity does not change because the same construction operations are required.

BOEING SPS

2.5-GW SPS: Independent Study

78-137



275 DAY CONSTRUCTION TIME
CONSTRUCT MONOLITHIC SATELLITE
MODULE, YOKE, AND ANTENNA CONSTRUCTED IN SERIES
SAME NUMBER OF CONSTRUCTION EQUIPMENT UNITS AS 10 GW SATELLITE LEO FACILITY
CREW SIZE: 478 FOR 100 DAYS, 350 FOR 175 DAYS

This Work Accomplished Using Boeing IR&D Funds

GENERAL FUNDING OBSERVATIONS

These preliminary observations indicate the primary impacts that may result from implementation of a 2.5 (rather than 5.0 or 10) GW SPS.

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SPS

General Funding Observations

78-138

- IF THE SPS DEVELOPMENT COST IS CONSIDERED TO INCLUDE FACILITIZATION AND THE FIRST UNIT (HENCE NEARLY $84 BILLION FOR THE 10 GW UNIT), THEN THE 2.5 GW UNIT OFFERS:
  - A LOWER FUNDING PROFILE, BY:
    - LOWER FIRST UNIT COST
    - DEFERRED DEVELOPMENT OF THE HLLV
    - LOWER FACILITIZATION COST (IF THE PRODUCTION RATE IS 2.5 GW/YEAR)
  - HIGHER TOTAL COST TO OBTAIN 10 GW ONLINE (FOUR UNITS)

PRELIMINARY SITING CONSIDERATIONS

Preliminary siting analysis within specific national areas (those covered by the three "contributing utility regions") under contract NAS9-15646 indicates that the smaller rectennas of the 2.5 GW SPS would allow approximately 50% more capacity to be sited after all "practical" 5.0 GW rectennas had been sited.

BOEING
SPS

Preliminary Siting Considerations
(Contract Funding)

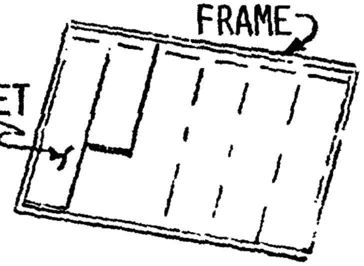
78-139

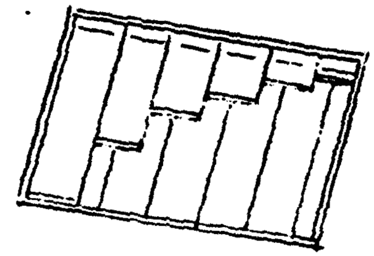
AFTER PLACING ALL PRACTICAL 5 GW RECTENNAS IN A FOUR-STATE AREA, AN ADDITIONAL 50% MORE POWER FROM SPACE CAN BE OBTAINED FROM THE 2.5 GW RECTENNAS, WHICH CAN BE SITED USING THE SAME GROUND RULES.

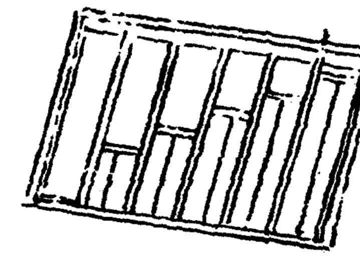
GRUMMAN

The following charts were presented by Grumman at the orientation meeting to describe their initial planning for investigation of construction alternatives.

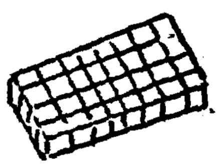
SOLAR ARRAY CONSTRUCTION IMPLICATIONS

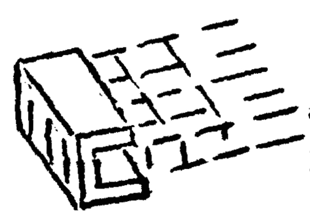


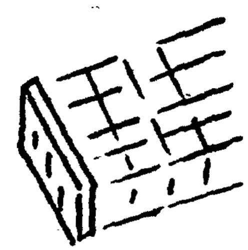


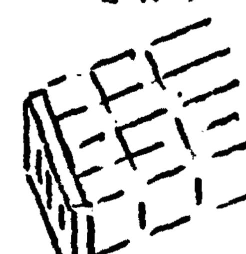


	BASELINE	WINDOW SHADE	GUIDED WINDOW SHADE
DEPLOYMENT METHOD	MANNED S.A. DEPLOY MACHINES (LEO & GEO)	REMOTE DEPLOY W/ UNFURL CABLE	REMOTE DEPLOY W/ UNFURL CABLE
UNIAXIAL SUPPORT	END TENSION	SUPT CABLES IN BLANKET	SEPARATE SUPT CABLES
DEPLOY/TENSION SEQ	COUPLED (TENSION AFTER DEPLOY)	DECOUPLED?	DECOUPLED (TENSION AFTER DEPLO
HEAVY EDGE MEMBERS (4 X 8 MODULE)	ALL (5 X 9)	2 X 4?	2 X 4
CONSTRUCTION JIG IMPACT	SUPT BEAM MACH & S.A. DEPLOY MACH	SUPT BEAM MACH & STRING CABLES	SUPT BEAM MACH & STRING CABLES
SOLAR ARRAY TRANS. IMPACT	FOLDED ARRAY	ROLLED ARRAY? W/ EDGE CABLES	FOLDED OR ROLLED ARRAY PLUS CABLES

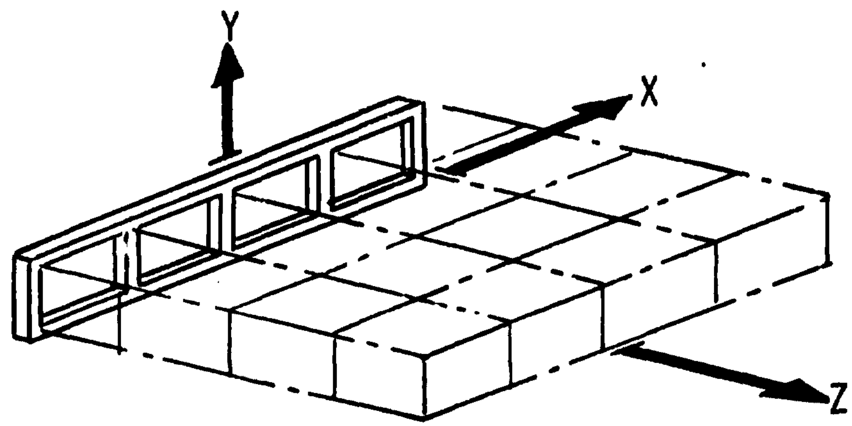








END BUILDER



CONSTRUCTION APPROACH

- o CONSTRUCTION ACTIVITY IS TAILORED TO THE X - Y PLANE.
- o ACTIVITY ALONG THE Z - AXIS IS LIMITED TO THE DEPTH OF THE FACILITY.

GRUMMAN

18

LEO CONSTRUCTION BASE: SIZE/SHAPE

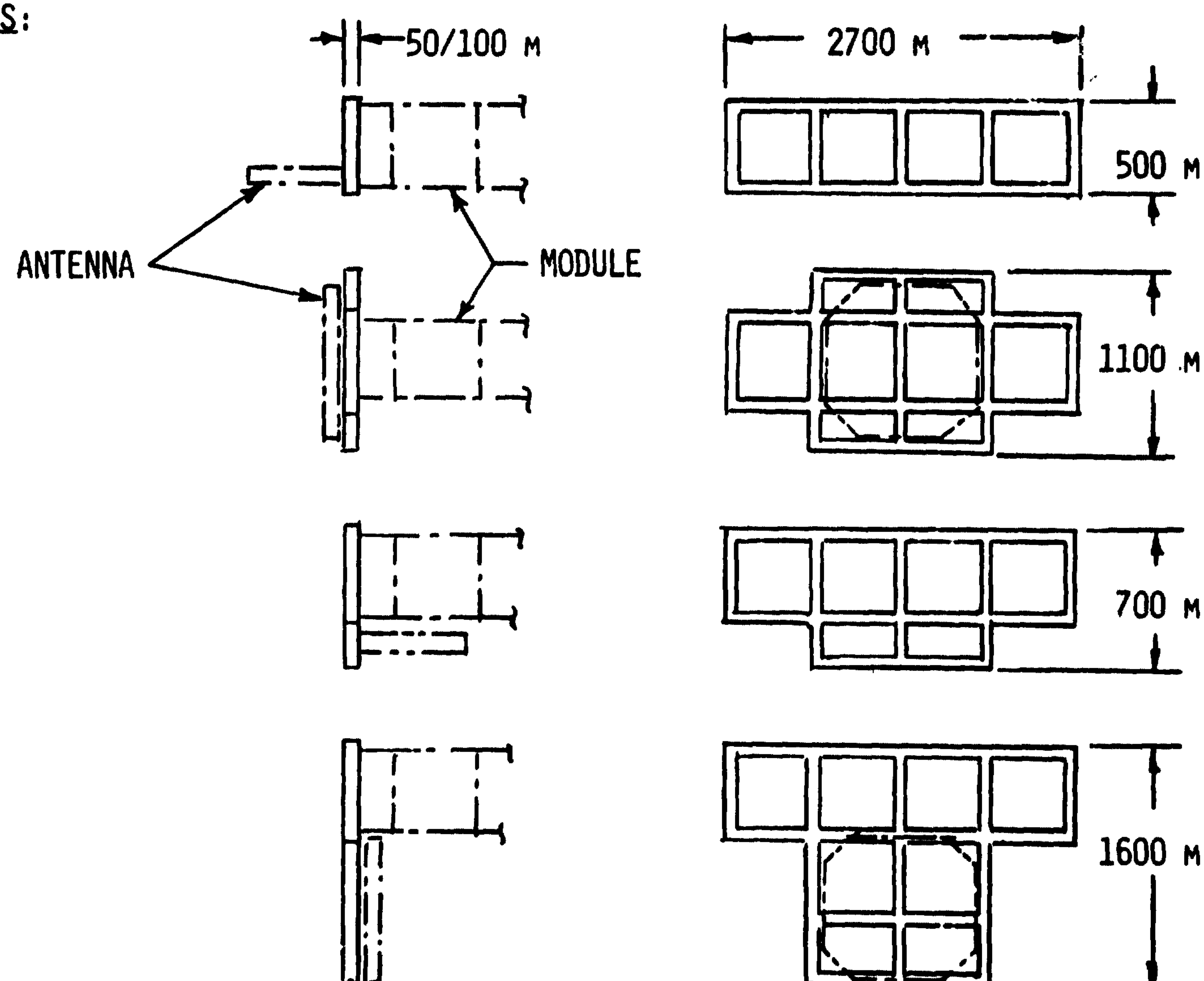
OPTIONS:

1.

2.

3.

4.



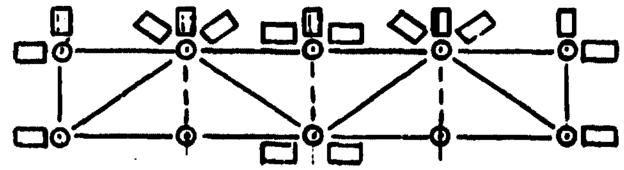
GRUMMAN

END BUILDER BEAM MACHINE OPTIONS

LATERAL

MACHINES

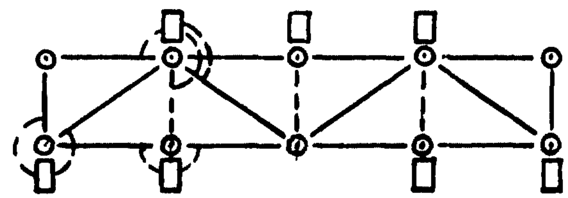
1. ALL FIXED



10 LONG.
17 LAT.

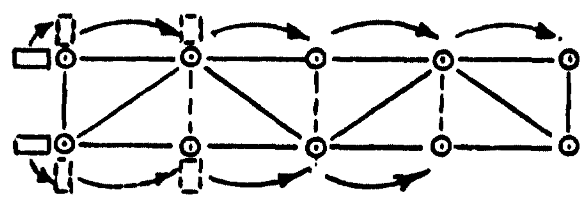
LONGITUDINAL

2. LATERALS GIMBALLED



10 LONG.
7 LAT.

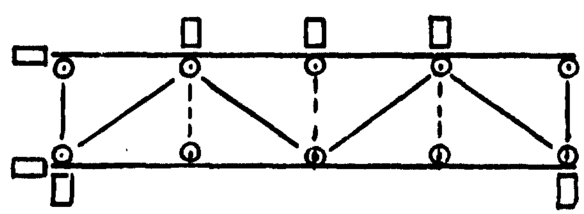
3. LATERALS MOVABLE



10 LONG.
2 LAT.

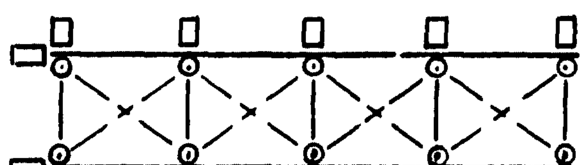
BASELINE SOLAR ARRAY MODULE FRAMES

TRANSVERSE FIXED - LATERALS GIMBALLED



10 LONG.
2 TRANS.
5 LAT.

FIXED & WIRED

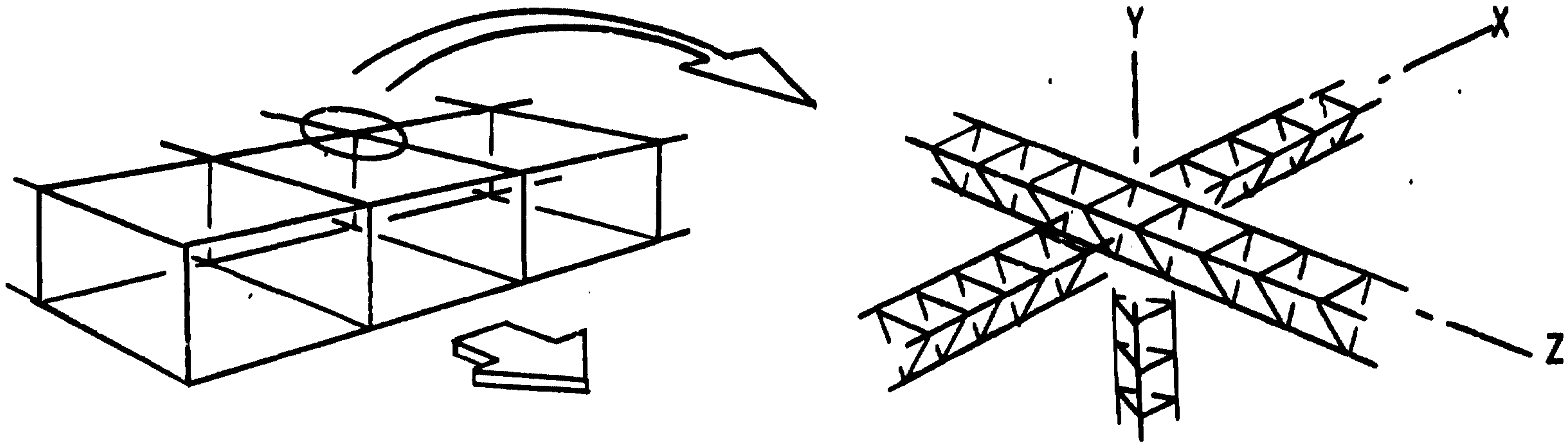


10 LONG.
2 TRANS.
5 VERT.

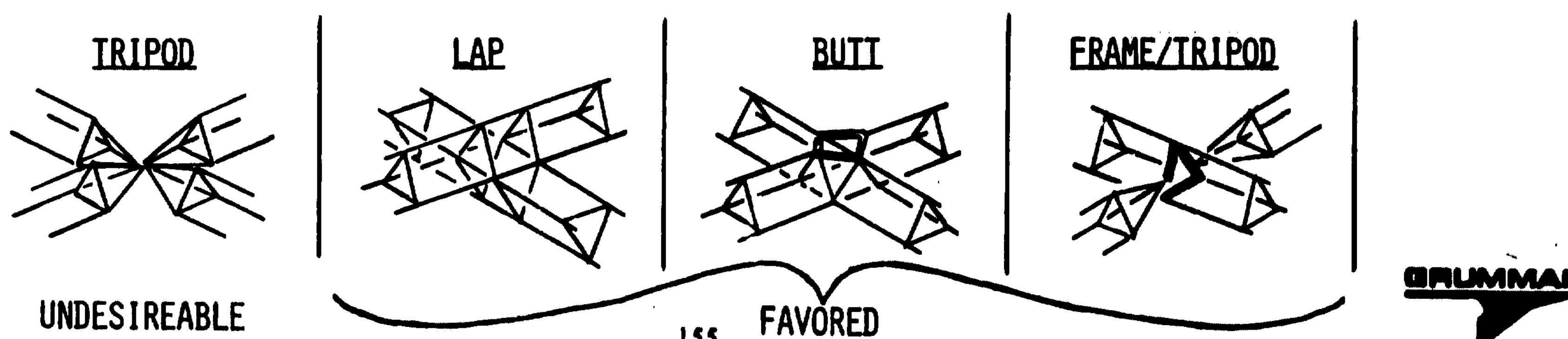
MODIFIED SPS FRAME

GRUMMAN

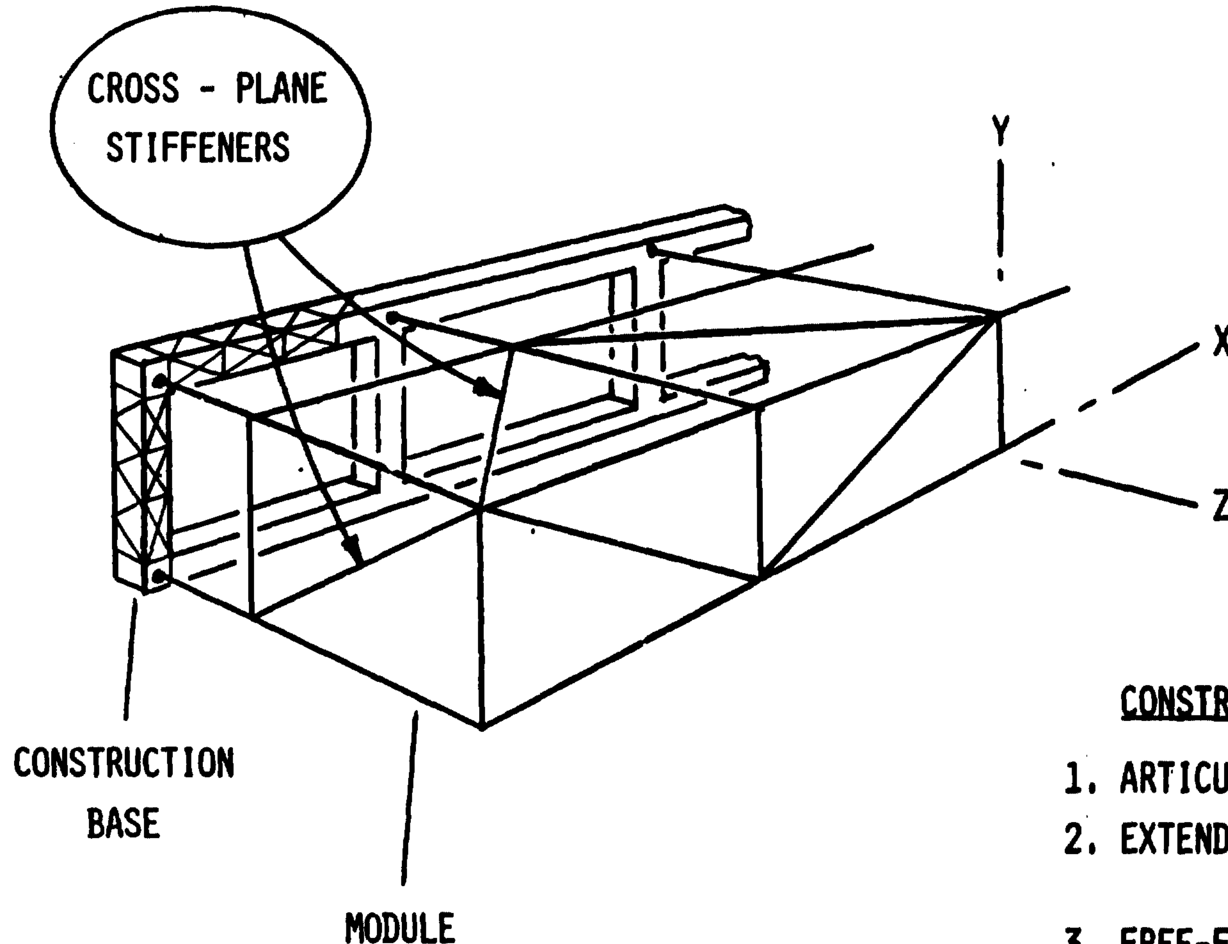
END BUILDING SPS STRUCTURAL JOINTS



JOINT CONFIGURATIONS



END BUILDING SPS CROSS PLANE STIFFENERS



CONSTRUCTION OPTIONS

1. ARTICULATING BEAM MACHINES
2. EXTENDED ARMS (UPPER & LOWER JOINING)
3. FREE-FLYER JOINING
4. TENSION WIRES

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TIMELINES - STRUCTURAL FAB & ASSY

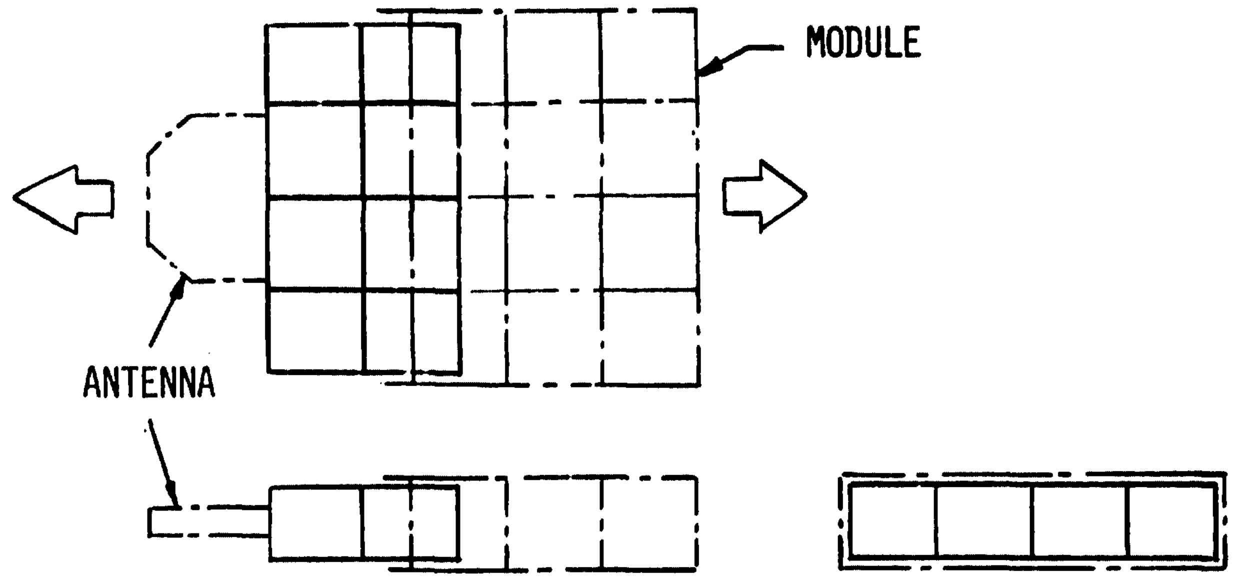
	BASELINE * ("C" CLAMP)	ALTERNATE ** (END-BUILDER)
1. END-FRAME	22.0 HRS.	7.3 HRS.
2. BAYS	52.0 HRS.	7.8 HRS. (V_I=5M/MIN) 11.5 HRS. (V_I=1M/MIN)
3. MODULE	488.0 HRS.	72.0 HRS. (V_I=5M/MIN) 146.0 HRS. (V_I=1M/MIN)

* BASELINE FABRICATION RATE 5M/SEC

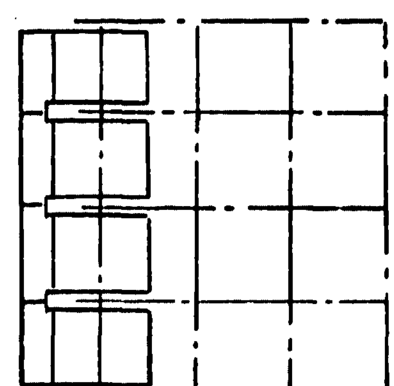
** 17 BEAM MACHINES

INTERNAL SYSTEM

OPTION 1



OPTION 2 (SLOTTED)



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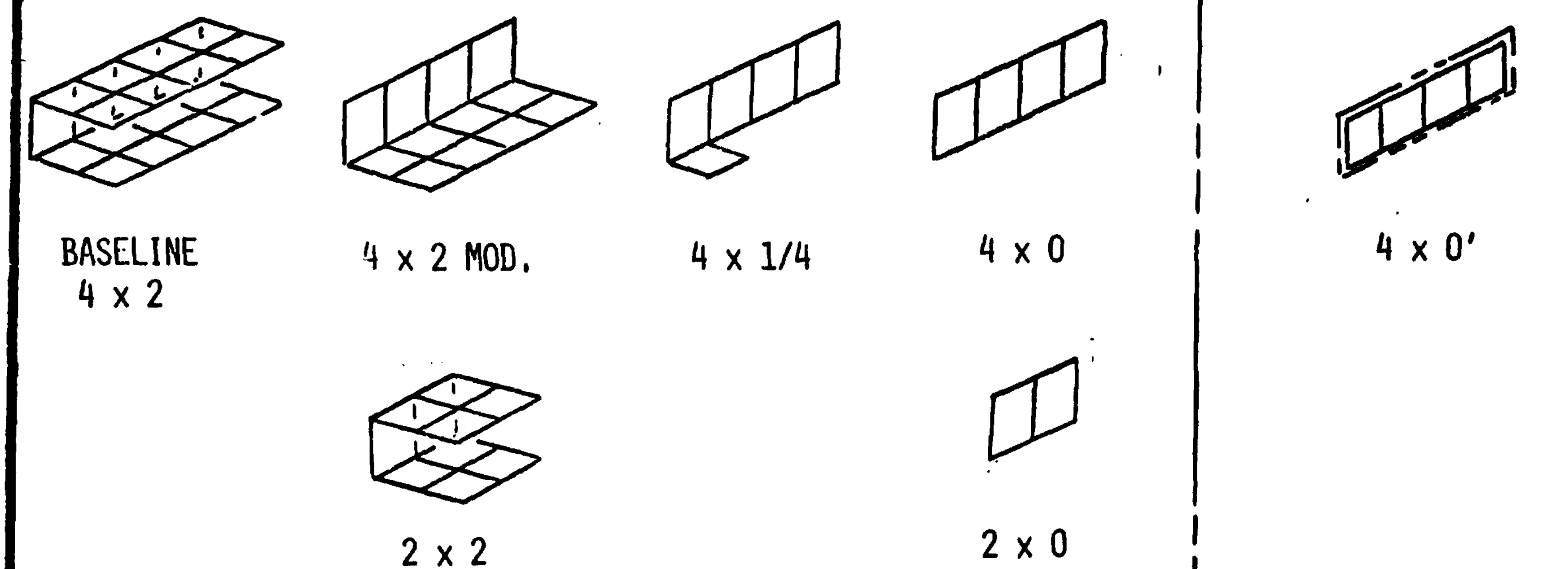
ALTERNATE LEO CONSTRUCTION BASES

- EXTERNAL SYSTEMS
- INTERNAL SYSTEM



MODIFIED SATELLITE - CONSTRUCTION OPTIONS

- o BOOTSTRAP CONSTR.
- o SMALL MODULE
- o SIMPLE ANTENNA

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ALTERNATE CONSTRUCTION CONCEPT EMPHASIS

- o BASELINE VS. END BUILDER (EXTRUSION), INTERNAL SYSTEM, & OTHERS

- o ALTERNATE BASE ARRANGEMENTS & CONSTRUCTION ELEMENTS
  - MODULE STRUCTURAL BUILD UP (BEAM MACHINES & CONSTR AIDS)
  - ANTENNA/YOKE BUILD UP & ASSY TO MODULES
  - SUBSYS INSTALLATION OPERATIONS (SOLAR ARRAY DEPLOYERS, MICROWAVE SUBARRAY DEPLOYERS, ETC.)
  - CREW SUPPORT

- o BASE/MODULE INTERFACE LOADS
  - SHEAR STIFFNESS
  - AXIAL LOAD EFFECTS (BEAM BUILDERS)

- o BASE BUILD UP & TECHNOLOGY REQMTS.

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